Faculty of Science and Engineering

Department of Civil Engineering

An Investigation into the Cement Content of Stabilised Pavement

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DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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ABSTRACT

Motor vehicles dominate Australia's transport system, for both travel and freight; consequently the road network in Australia is of critical importance to the social and economic welfare of our nation and to national and regional growth. About 90% of this network is constructed of compacted unbound granular materials with thin bituminous seals. Many of these granular pavements were not designed to carry the current traffic volumes or increased axle mass loadings; and are therefore highly likely to require some form of remedial works in the near future.

Stabilisation with cement is becoming increasingly important as a means to upgrade or recycle existing materials in deteriorated pavements due to the economic, social and environmental benefits. With limited road maintenance funding and increasing heavy vehicle axle loads reducing pavement life; cementitious stabilisation is an ideal low-cost pavement rehabilitation technique that can improve the strength and durability of the overlying pavement materials and thereby enhance traffic carrying capacity over a longer period of time.

It is advantageous to know the cement content of the improved material to ensure an appropriate design and to predict the future performance of the pavement. Being able to determine the cement content of stabilised basecourse is also an important diagnostic tool which can be used to help ascertain the cause of failures. Various methods for determination of the cement content of basecourse material are currently specified in road construction projects to verify that the requisite levels of stabilisation are achieved. These methods however are limited by the variability of the pavement materials and the costs and delays associated with test procedures.

An investigation into the determination of the cement content of stabilised road base was undertaken utilising a test method trialled in 2009 in order to develop and validate the method.

A range of typical Western Australian basecourse materials were assessed when stabilised with General Purpose cement. They included limestone and crushed rock base from the Perth Metropolitan area; scree gravel from the Pilbara region; high

plasticity index (PI) gravel from the Wheatbelt region; and lateritic gravel from the Midwest region.

The main focus areas were to confirm the suitability of the method for testing of cement content in more extreme road base materials; and to establish the long term veracity of the test method by testing samples at increasing hydration periods.

Following the laboratory testing of the limestone samples it was concluded that the test method is not considered suitable for testing on granular pavement material with either; a high calcium carbonate content or granular pavement material whereby the material reacts strongly with hydrochloric acid to the extent that more than 10 % of the original mass is consumed.

Testing based on the results obtained for the Mid-West Lateritic Gravel and the Wheatbelt North High PI Gravel samples indicate that the test method is reliable for these materials at one month hydration. However the predicted cement content values achieved for the Pilbara Scree Gravel samples and the Crushed Rock Base samples at one month hydration and were not consistent with the actual cement addition.

The predicted cement content values achieved for all tested basecourse types then showed a marked decrease over the 3, 6 and 12 month hydration periods and it was therefore concluded that the test method is not suitable for cement content determination where the hydration period is three months or longer.

Further testing utilising the test method is recommended as continued research into stabilisation processes should be promoted as they can potentially improve the performance and the cost of maintaining and upgrading the road network, which is vital for the continued growth, prosperity and well-being of the Australian nation.

ACKNOWLEDGEMENTS

This thesis is part of a research project on an investigation into the cement content of stabilised pavement. The research has been carried out at Main Roads Western Australia (MRWA), whilst working as a pavement engineer at Materials Engineering Branch (MEB). I would like to acknowledge and thank the following individuals who have supported me in my endeavours.

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1. INTRODUCTION

1.1 Objectives and Scope

The proposed research programme is an in-depth investigation into the determination of the cement content of stabilised road base utilising a test method trialled in 2009. Impetus for the research is provided by the need for improved stabilisation methods in order to enhance pavement performance.

In particular this research aims to:

i) Conduct a preliminary study into stabilisation practices and the methods currently adopted for the determination of cement content.

ii) Perform testing on modified road base materials typically used in Western Australia to determine the range of application and establish the reliability of the test method.

iii) Analyse the test data using statistical analysis techniques to verify methods used and determine the reliability of the test method.

1.2 Background

For the last 25 years floodway pavements on regional roads in Western Australia have routinely been stabilised with cement where water ingress is a problem; since unstabilised basecourse subject to inundation during the wet season will shear fail when it becomes saturated during flooding. It is also used to improve marginal quality materials when the cost of supplying compliant material to project sites is high (Keeley, 2008).

Cement stabilisation is also used on major highways and in urban areas where pavements have exhibited signs of structural failure of the granular basecourse layer; and is the repair method of choice in rural areas as it provides the simplest, cheapest solution in terms of both cost and time.

In Western Australia cement addition to achieve a modified basecourse layer is typical due to cracking problems in the asphalt surfacing associated with thin bound pavement layers.

To ensure that the modified basecourse materials perform as expected it is specified by Main Roads Western Australia (MRWA) that the quantity of cement added to the pavement material is approximately 1-2% by dry mass of basecourse material. If is too low the pavement will be too weak, flex excessively and fatigue asphalt surfacing; if it is too high the pavement will become bound and fatigue crack under trafficking as can be seen in Figures 1-1, 1-2, 1-3, and 1-4.

Figure 1-1: Fatigue cracking of asphalt surface over stabilised basecourse on Great Northern Highway at West Swan Road intersection.

Figure 1-2: Detail of fatigue cracking in wheel paths on Great Northern Highway at West Swan Road intersection.

Figure 1-3: Block cracking of stabilised basecourse reflecting through to asphalt surface on Tonkin Highway approaching Gosnells Road West.

Figure 1-4: Detail of block cracking on Tonkin Highway approaching Gosnells Road West.

Various methods for determination of the cement content of basecourse material are currently specified in road construction projects to verify the requisite level of stabilisation is achieved. These methods however are limited by the variability of the pavement materials and the costs and delays associated with test procedures.

MRWA does specify process control to manage the practice of adding cement to gravel or crushed rock base (CRB), whether it is plant mixed at a quarry or spread on the road and mixed in-situ; however they currently do not have a procedure to determine the actual percentage of cement added to pavement material.

In late 2008 MRWA commenced developing a test to determine the quantity of cement added to the pavement material during stabilisation. Trials of the test method for in-situ applications were conducted in 2009 on three basecourse materials typically used in the Perth metropolitan area with positive results.

Further testing of modified road base materials using the test method trialled was recommended to verify the scope and reliability of the test method.

The test for cement content will be aimed at providing rapid feedback to construction crews on the effectiveness of their cement addition process during pavement construction and longer term as a tool for maintenance teams so they can assess whether the cement content is a mitigating factor in pavement failure.

This investigation involves extension research on the test method developed in 2009 for determination of the cement content of stabilised basecourse material.

1.3 Significance

Motor vehicles dominate Australia's transport system, for both travel and freight; consequently the road network in Australia is of critical importance to the social and economic welfare of our nation and to national and regional growth.

The road network consists of around 900,000 km of paved roads; 70% forming the rural network and 30% the urban network. The replacement value of the road pavement part of this asset is in the order of $A50 billion (Youdale, 1996).

About 90% of this network is constructed of compacted unbound granular materials with thin bituminous seals. Many of these granular pavements were not designed to carry the current traffic volumes or increased axle mass loadings; and are therefore highly likely to require some form of remedial works in the near future.

The construction and rehabilitation of granular pavement using cementitious stabilisation methods is becoming increasingly viable due to lower capital costs, improved long term performance and minimal disruption to the existing environment.

Continued research into stabilisation processes that can potentially improve the performance and the cost of maintaining and upgrading the road network are vital for the continued growth, prosperity and well-being of the Australian nation; and research into test procedures specific to stabilisation is vital to ensure that the

stabilised pavement will perform as expected and to help improve existing stabilisation techniques.

The result of this research will specifically yield:

- Improved test regimes to ensure that the desired levels of cementitious stabilisation are achieved;
- Improved diagnostic procedures for cement stabilised pavement failures.

When the results are applied, they will:

- Improve pavement cementitious stabilisation procedures;
- Improve highway and road construction methods relating to cementitious stabilisation;
- Improve the quality of highways and roads in service across Australia.

1.4 Thesis Outline

This report contains six chapters. Chapter 1 presents the objectives and scope of the research. Chapter 2 gives an overview of the history and outlines the fundamental knowledge surrounding pavement stabilisation practices in Australia. The experimental methodology utilized in the research is described in Chapter 3. Chapter 4 provides the test results associated with this research, including a discussion of the results and the challenges encountered. Chapter 5 gives a summary of research findings and Chapter 6 outlines recommendations for further research.

To achieve the objectives of this research, the study was carried out using the following methodology.

Literature review

For the first stage of the research a review of the literature relevant to cementitious stabilisation practices in Australia was undertaken. The research considered the history of stabilisation; its role in pavement rehabilitation; and outlined the social, environmental and economic benefits. The research also explored the current

approaches used to determine the cement content of stabilised pavement in order to apprise the existing body of knowledge available.

Experimental Work

In the second stage the following experimental work was conducted to determine the range of application and establish the reliability of the test method:

Determine any limitations of test method.

- Testing was conducted on crushed limestone and high PI road base material to determine the suitability of the method for testing of cement content in more extreme road base materials.

Establish long term veracity of test method.

- Testing was conducted at 1, 3, 6, 12 month hydration periods to determine the validity of the test method over time. The long term testing was conducted on four representative basecourse materials from across WA.

Data Analysis

The third stage was to analyse the laboratory test results using a range of statistical techniques. These techniques included simple analysis of the test results to verify test procedures and for assessment of the reliability of results; and the use of regression analysis to examine any trends in the data.

- Mean values will be used in cement content verification.

- The standard deviation, Z scores and confidence interval estimate will be calculated to give an indication of the variability of the results.

- Linear regression analysis will be used to fit a predictive model to the test data and the fitted model will be used to make a prediction of the cement content of the test sample. Linear regression analysis will also be applied to quantify the strength of the relationship between the data sets.

Conclusions and Recommendations

The final stage of the thesis project involved providing a summary of the conclusions drawn from the experimental work and outlining the recommendations for further research.

2. BACKGROUND

2.1 Introduction

This section presents a review of the literature relevant to the cementitious stabilisation of new and existing pavement and is principally concerned with Australian practices and procedures.

Initially a brief overview of pavement and pavement types and their behaviour under load is presented, with the attention being on the workings of flexible pavement.

The overview is followed by a discussion of the methods used to stabilise flexible pavements and the binding agents involved; however as the focus of the research is confined to stabilisation with cementitious materials the mechanics of cementitious stabilisation are explained more fully and the stabilisation of granular pavement materials using other binding agents are only briefly referred to. The advantages of modified pavements over bound pavements that are treated with higher percentages of cement are also considered.

The research then goes on to give an outline of the history of cementitious stabilisation practices and their development in Australia and how this has influenced stabilisation practices in Western Australia. The significance of cementitious stabilisation in the rehabilitation of existing pavement and its importance as a means to upgrade or recycle existing materials in deteriorated pavements is then discussed and the subsequent social, environmental and economic benefits of rehabilitation are appraised.

Finally a review of the methods currently adopted for determination of cement content by Australian Road Authorities and within Main Roads Western Australia was carried out in order to assess the existing body of knowledge available.

2.2 Pavement

A pavement is usually a combination of several layers of suitable material placed on top of the in-situ soil (subgrade) so that vehicle loads from traffic can be transmitted safely to the subgrade without failure or excessive damage affecting the working condition of the road surface or pavement layers during their intended lifespan (Figure 2-1).

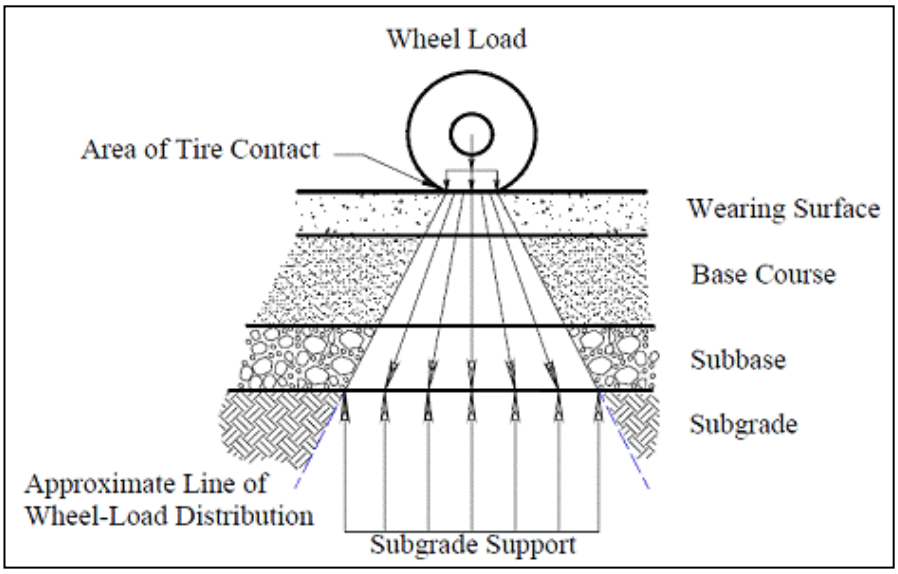

Figure 2-1: Distribution of load stress in flexible pavement (The Constructor)

Pavements are classified as either flexible (containing unbound granular and/or stabilised materials and/or asphalt) or rigid (concrete pavement with joints and/or steel reinforcement) (Austroads, 2005).

The term 'flexible pavement' is used to describe pavement construction other than those described as rigid pavements, including unbound granular pavements with thin bituminous surfacings and pavement incorporating bound layers such as stabilised granular material and asphalt. A rigid pavement consists of a plain, reinforced or prestressed concrete base (usually 30 MPa or more) overlying a sub-base material. Typical sub-base materials used include lean mix concrete, cement stabilised crushed rock, and unbound granular material (Austroads, 2005).

Under load a flexible pavement deforms (bends and deflects) and horizontal tensile strains and vertical compressive strains are produced in the pavement layers in response to the load as shown in Figure 2-2a. The load applied to rigid concrete pavements results in a more uniform distribution of strain on the subgrade as shown in Figure 2-2b.

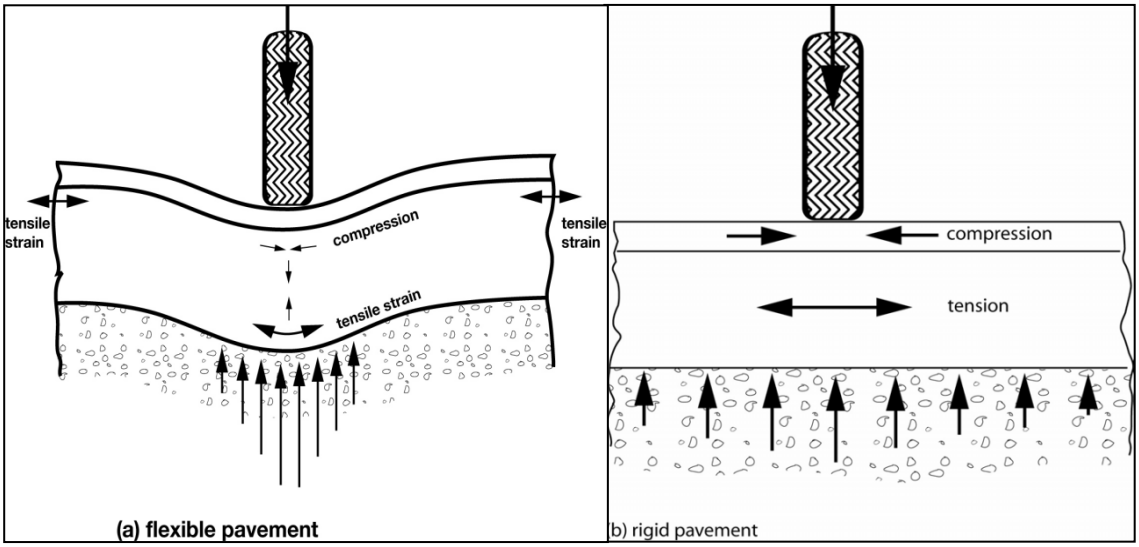

Figure 2-2a and 2-2b: Responses of different pavement types to load (Austroads, 2005).

As this research project is concerned with the stabilisation of gravel layers in flexible pavement the focus of this paper will be confined hereafter to flexible pavement and rigid pavement will not be discussed further.

2.3 Flexible Pavement

Flexible pavement typically consists of bound, modified or unbound natural gravel layers underlying either asphalt or a thin bituminous surfacing (Figure 2-3).

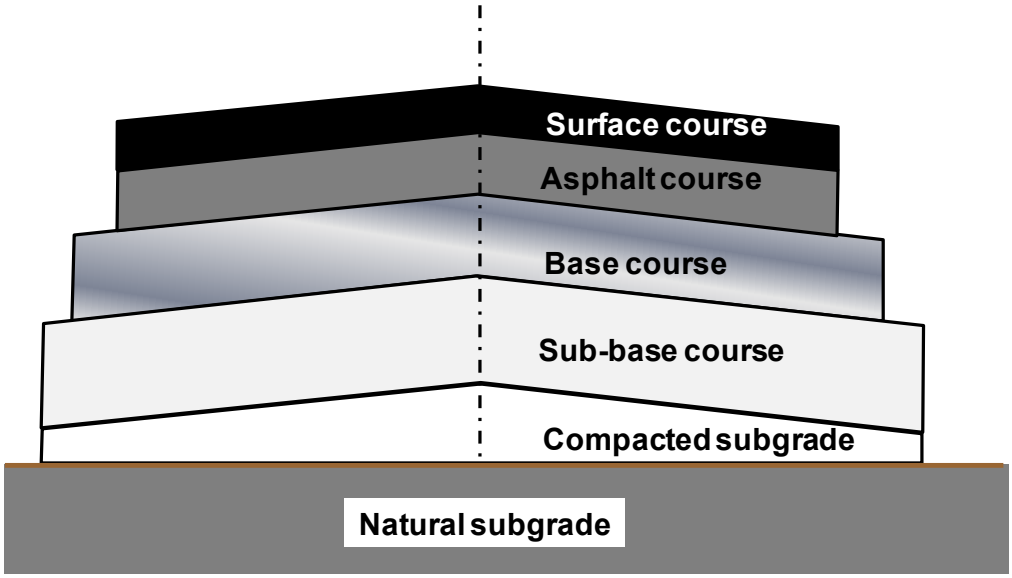

Figure 2-3: Typical cross section of a flexible pavement where a combination of the above layers can be used.

Flexible pavements, composed of unbound granular materials as a basecourse layer with thin bituminous surfacings, are used to surface nearly 90% of Australia's road network (ARRB, 2011) and are widely used in Western Australian pavements.

In flexible pavements with unbound granular layers the basecourse layer provides the bulk of the structural capacity in terms of load-spreading ability within the pavement (Austroads, 2007). These pavements are generally constructed with better quality and therefore stronger material in the basecourse layer where the intensity of the compressive stress is high, and lower quality materials in sub-base courses where the intensity is low. The load bearing strength of the unbound granular layers is provided by the aggregate interlock between particles (Araya, 2011).

When either suitable high quality basecourse materials are unavailable or prohibitive in terms of cost, or an unbound granular pavement has reached the end of its structural life due to age and/or traffic volumes exceeding the capacity of the

pavement, stabilisation techniques can be used to improve the granular material. They can be used to improve the strength and stability of lower quality materials that are readily obtainable or the existing pavement layers can be strengthened by in-situ stabilisation. Stabilisation techniques can be used to improve the bearing capacity of the existing unbound granular layers whilst seeking to reduce both costs and the use of new materials (PIARC, 2003).

2.4 Pavement Stabilisation

Stabilisation may be defined as a process that improves the load bearing capacity and/or stability of a material. It is the improvement of a soil or pavement material and is typically categorised based on the type of material to be stabilised and the desired performance (Austroads, 2005). Pavement stabilisation is used widely in both the construction of new roads and the rehabilitation or recycling of existing roads worldwide.

The methods used to stabilise pavements in Australia include;

- Subgrade stabilised materials.
- Granular stabilised materials.
- Modified stabilised materials.
- Bound stabilised materials.

Granular stabilisation involves the blending of various pavement materials without a binder; however basecourse stabilisation is usually achieved through the addition of a small quantity of binder - 1% to 4% (Smith & Vorobieff, 2007), to achieve a modified or bound state after binder addition as defined by Table 2-1.

Table 2-1: Typical levels of stabilisation (Austroads, 2006)

Category of Stabilisation	Indicative laboratory strength after stabilisation
Subgrade	$CBR^1 > 5\%$ (subgrade and formations)
Granular	$40\% < CBR^1 < 100\%$ (sub-base and basecourse)
Modified	$0.7\ MPa < UCS^2 < 1.5\ MPa$ (basecourse)
Bound	$UCS^2 > 1.5\ MPa$ (basecourse)
Notes:	1. 4 day soaked CBR 2. Values determined from test specimens stabilised with GP cement and prepared using standard compactive effort, normal curing for a minimum of 28 days and 4 hour soak conditioning.

Stabilisation typically involves the addition of lime, bituminous or cementitious binding agents such as cement, fly ash or slag, alone or in combination to the subgrade or basecourse material (Austroads, 2005). Stabilisation using cementitious binding agents is one of the more common chemical stabilisation techniques used around Australia (Williams, 1986).

As the focus of this research project is on stabilisation with cementitious materials any reference to stabilisation will be referring to cementitious stabilisation, with the stabilisation of granular pavement materials using lime and bituminous products being beyond the scope of this research.

2.5 Cementitious Stabilisation

Cementitious stabilisation refers to stabilisation of a normal unbound gravel pavement layer using either cement alone or with additional cementitious materials. The design intent is to either turn the gravel pavement layer into a modified

pavement layer which is considered an unbound or flexible layer by using up to 2% by volume of cementitious material, or a bound or rigid layer with cementitious stabilisation of 3% or greater by volume of cementitious material.

Cement is used to modify the basecourse material to improve performance under load. The addition of cement reduces plasticity and provides cementitious bonds that contribute to improved performance by increasing shear and bearing strength (Main Roads WA, 2003a).

Until recently, the cementitious binder most commonly used was general-purpose (GP) cement; however since the 1990's a host of other binders have been developed which are typically adopted for cementitious stabilisation including General Blend (GB) and Low Heat (LH) cement powders and different blends of fly ash and blast furnace slag binders (Wilmot, 1994).

As the binders behave differently on each different host material, matching of the binder to the material is very important. AustStab and Australian Road Authorities have released guidelines to assist in matching the binder to the host material, and it is common practice to now use binders consisting of blends of cement and what were previously waste products, such as fly ash and blast furnace slag binders. Blends of slag, fly ash and cement are useful for achieving maximum performance from a large range of pavement materials. Their inclusion has increased the scope of stabilisation to allow pavements to be stabilised to greater depths, has allowed the use of a greater range of possible soils in pavement construction and improved construction practices through the increased workability and slower setting times of the stabilised material (Wilmot, 1994).

Cementitious stabilisation techniques are highly beneficial for improving pavement performance in areas where the sub-grade or available in-situ materials are expansive, weak or wet (Austroads, 1996). They can also be used to improve basecourse resistance to deformation in areas subject to high rainfall.

They can be adopted in situations where the pavement is exhibiting signs of structural failure. Either because it has reached the end of its design life or rising traffic volumes and axle loadings have increased beyond the structural capacity of

the pavement and contribute to pavement failure. Cementitious stabilisation of the basecourse layer can improve its strength and durability and thereby enhance the traffic carrying capacity of the pavement over a longer period of time (Little & Nair, 2009).

Cementitious stabilisation can be used to provide cost-effective new pavement construction through the inclusion of stabilised pavement layers or used to improve/rehabilitate existing pavements by in-situ stabilisation and allows enhancement of both standard and substandard basecourse and subgrade materials to levels consistent with the required design life of the pavement.

2.6 Modified Pavement

Pavements are considered to be modified pavements when the percentage of cement added is 2% by dry mass of the basecourse material or lower, and are believed to have some advantages over pavements that are treated with higher percentages of cement. The advantages can be summarised as follows;

- There is less reliance placed on the binder for long term performance by improving grading and Plasticity Index.
- Allows the optimisation of the blend of cementitious binders to suit the granular material type and available working time.
- For design purposes modified pavements are treated as an unbound flexible pavement when using the mechanistic pavement design approach.
- Significantly reduces reliance on bonding between layers when constructing deep lifts; whereas bonding is critical between layers of stabilised pavements that have higher percentages of cement.
- Minimises the likelihood of shrinkage cracking.
- Avoids creating a bound layer within the flexible pavement that is more susceptible to fatigue cracking (Vorobieff, 2004).
- Is less sensitive to increased axle loadings than a bound layer.

The material characteristics that affect the actual fatigue performance of stabilised materials include cement content (Litwinowicz and Brandon, 1994). Therefore it is essential for pavement designed with modified layers that the quantities of cement added to the pavement material are not too high because the pavement will become bound and can cause the pavement to fatigue crack under traffic loads. Neither can the quantity of cement added to the pavement material be too low as this will result in the pavement being too weak; able to flex excessively and fatigue the asphalt surfacing (Adaska & Luhr, 2004).

2.7 History of Cementitious Stabilisation in Australia

Cementitious stabilisation techniques were introduced and have been used in Australia since the 1940's for pavement construction and rehabilitation (RTA, 2004). The use of stabilisation became increasingly popular during the fifties and sixties on the Eastern coast of Australia; however in the in the late sixties early pavement failures in in-situ stabilised pavement, due to poor construction practices, resulted the closure of a number of companies and a resulting move away from cementitious stabilisation as a viable approach (Wilmot, 1996).

Stabilisation practices then re-emerged in the early 1970's and became popular again initially on the East coast through Queensland, New South Wales and Victoria. By the late 1970s cementitious stabilisation had also been introduced into South Australia and Western Australia (Vorobieff, 1998). During this period until the early 1980s pavement research concerning cementitious stabilisation was conducted in a fairly uncoordinated way by the State Road Authorities and the Australian Road Research Board (Youdale, 1996).

For the next decade the use of stabilised pavement layers to construct and rehabilitate roads continued to be used throughout Australia; however the stabilised thickness of individual layers was restricted to 200 mm or less as adequate binder distribution and compaction was not yet achievable with greater depths (ARRB, 1996). The restrictive use of thin layers was thought to contribute to poor pavement performance

which drove the subsequent push for a greater understanding of the performance of stabilised materials and the development of improved plant and equipment.

Since 1990, Austroads, in association with various industry groups, have undertaken extensive research and pavement studies incorporating the use of stabilised material in flexible pavements. Significant research carried out during the 1990's included the Road Rehabilitation by Recycling Project (also known as the GIRD Project) carried out in South Australia from 1992 to 1995, and the Accelerated Loading Facility (ALF) trials concerning the performance of cementitious materials carried out in New South Wales and Victoria between 1994 and 1998 (Vorobieff, 1998).

The Road Rehabilitation by Recycling Project involved a range of laboratory and field research projects where the performance of three major trial pavements, containing cementitious binders blended with soils from across Australia, was monitored.

The Accelerated Loading Facility (ALF) is used to simulate heavy vehicle trafficking on pavement structures under controlled conditions. The NSW ALF trials at Cooma and Eraring were to monitor the performance of deep-lift recycled pavements and cement-stabilised fly ash pavements respectively. The Victorian ALF trials in Dandenong involved monitoring the performance of pavement constructed using different binders in poor quality soil.

The outcomes of this research have been a better understanding of the structural capacity of stabilised pavement material, its durability and its predicted performance (Youdale, 1996).

The last few decades has also seen the continued development of sophisticated plant and purpose-built equipment; incorporating the ability to achieve greater stabilisation depths in a single pass (depths to 400 mm of stabilisation in a single layer), better spreader capacity and more reliable technologies to help ensure accurate measurement and placement of the binder. These advances have led to improved construction practices, fewer construction risks and resulted in greater pavement reliability. Subsequently the viability of stabilisation practices has progressed from

the rehabilitation of local government low-traffic roads through to major roads and highway construction.

These technological advances combined with the extensive research and pavement studies have led to an improvement in stabilisation practices in Australia and therefore stabilisation techniques being used more frequently for remedial and construction works.

The credibility of stabilisation practices is evidenced by State Road and Local Government Authorities across Australia providing stabilisation techniques and procedures for improving basecourse materials in their in-house manuals for pavement design and construction. Organisations such as Austroads and AustStab also distribute guides outlining recommended stabilisation techniques and procedures, and along with interested industry groups collaborate with State Road Authorities to help ensure available knowledge and information is shared and meets current best practice.

Local Government authorities in particular have used cement stabilisation as a means to recycle aged or failing granular pavements. Hodgkinson noted that cement stabilisation has been used as a road asset management tool by approximately 60 Local Government Authorities due to its good long-term performance. He found that roads recycled by cement stabilisation have a 75% or greater probability of exceeding the expectations of flexible granular pavement (Hodgkinson, 1991).

2.7.1 Stabilisation in Western Australia

For the last 25 years floodways on regional roads in Western Australia have routinely been stabilised with cement either during construction or as a repair option. The cement improves basecourse resistance to deformation in these areas where water ingress is an ongoing problem.

Cement stabilisation of the basecourse layer for pavement strengthening is also the repair method of choice in rural areas as it provides the simplest, cheapest solution in terms of both cost and time. This is often because rural roads in Western Australia are isolated and material haulage is costly. In addition rural roads tend to be single carriageway; single lane roads and resurfacing with an asphalt overlay would need to

be done the full width of the carriageway to maintain the road profile; while stabilisation of the basecourse allows the repair to be undertaken at the failure location alone.

Cement stabilisation has also been used on major highways and in urban areas where pavements have exhibited signs of structural failure of the granular basecourse layer.

In particular cementitious stabilisation is used on lateritic gravel and ferricrete basecourse. Lateritic and ferricrete gravels are considered to be the best naturally occurring gravels for basecourse and sub-base material in Western Australia. Many of these types of gravels are well graded and have similar strength characteristics and durability as basecourse manufactured from crushed rock (Emery et al, 2007). Their suitability and widespread availability (Figure 2-4) ensures they are routinely used as basecourse materials in Western Australia. Cementitious stabilisation of these gravels is preferred due to the material properties and rounded (pisolitic) shape of the gravel being compatible with this process.

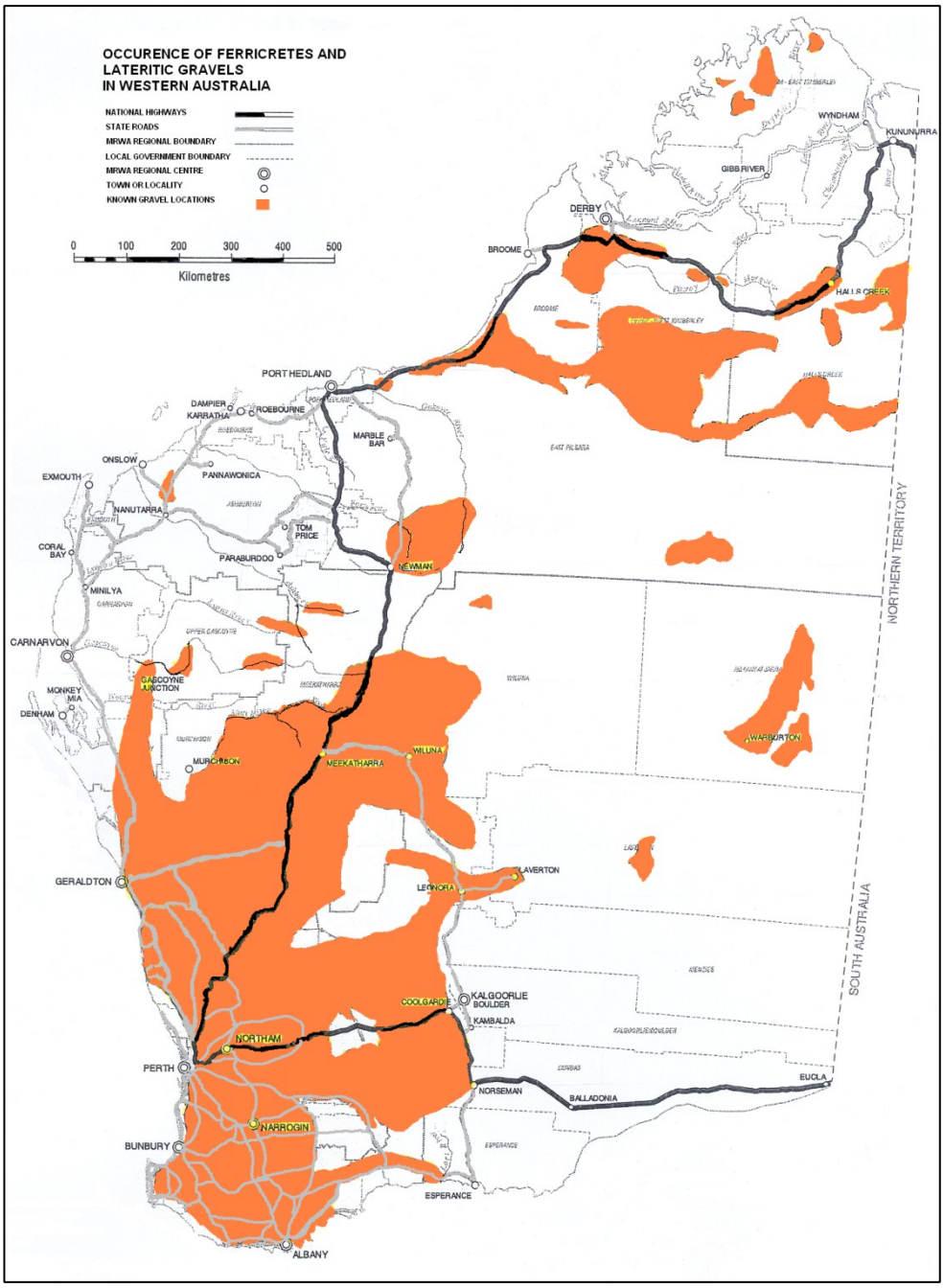

Figure 2-4: Distribution of Lateritic Gravel in Western Australia (Main Roads WA, 2003a).

Based on 1: 250 000 Geological Map Series. Geological Survey of Western Australia.

Cement stabilisation of the lateritic gravel basecourse was the rehabilitation strategy adopted by Main Roads WA for a major Perth metropolitan highway when a section of the highway had failed; evidenced by rutting, cracking and potholing (Figure 2-5).

Figure 2-5: Failure section evidenced by rutting, cracking and potholing on Great Eastern Highway, August, 2011

The recommended maintenance option for the failure section depicted in Figure 2-5 was to stabilise the existing asphalt and lateritic basecourse layer to 280 mm with 1.5% Low Heat (LH) cement and resurface with dense graded asphalt.

Cementitious stabilisation in WA has met with varying degrees of success. Poor performance of the stabilised pavement is generally because of poor design and construction practices.

Poor design practices include;

- Stabilisation of pavement layers which are too thin - due to incorrect use of the mechanistic design process.
- The selection of an inappropriate stabiliser for the basecourse material.
- Specifying an incorrect amount of stabiliser - generally too much cement.
- Failure to establish the actual thickness of layer to be stabilised so that poor quality material is included.

Poor construction practices include;

- Insufficient compaction of stabilised layer.
- Insufficient or lack of dryback before surfacing.
- Poor mixing of the binder and basecourse material.

(Keeley, 2004)

2.7.2 Australian Influence

Tom Wilmot, President of Auststab reveals that Australia is at the forefront of stabilisation theory and application worldwide, with Australian technology being used in Europe and Asia to improve stabilisation techniques in those areas. He also notes that spreaders developed and used in Australia are the most accurate and advanced in the world and that our knowledge has assisted in the development of new equipment coming out of America (Wilmot, 1996).

Stabilisation methods and technology used on South Australian roads have been successfully adapted and trialled in India. Trial sections of contemporary pavement using in-situ stabilisation technology were constructed to contrast against traditional Indian construction. The results were favourable in terms of significant

improvements in recorded deflections which corresponded to increased pavement life (Andrews & Dey, 1998).

Studies conducted by Main Roads WA to investigate ways of using stabilisation to improve the strength of crushed rock base have led to interest from New Zealand (NZ). Concerned about early failures of granular pavements in NZ, Dr Greg Arnold and Alan Kirby headed a field trip to Perth to learn about testing and performance of Hydrated Cement Treated Crushed Rock Base (HCTCRB). The positive results generated from the studies conducted by Main Roads WA and further testing conducted in NZ have led to interest from Transit New Zealand on the use of HCTCRB. It has been proposed that HCTCRB be used in NZ for high trafficked roads and as a way of upgrading inferior local materials for use as basecourse (Arnold & Kirby, 2007).

2.8 Pavement Rehabilitation

Stabilisation is becoming increasingly important as a means to upgrade or recycle existing materials in deteriorated pavements. Australia's road network consists of 900,000 km of paved roads worth around 300 billion dollars. About 90% of this network is constructed of compacted unbound materials with thin bituminous seals and the majority of the network is now well over 25 years old. Many of these pavements were not designed to carry current traffic volumes and increased axle mass loadings and are highly likely to require some form of remedial works in the near future. Rehabilitation of the existing pavements by using cementitious stabilisation is becoming an increasingly viable alternative to other common rehabilitation methods (Smith & Vorobieff, 2007).

Cementitious stabilisation and the more typical rehabilitation methods can be summarised as follows;

Sprayed seals - reseal

Sprayed seals typically consist of one coat of bituminous binder followed by the application of a layer of cover aggregate. A 'reseal' is the term used to describe the application of a sprayed seal over an existing seal.

Although a very economical method of rehabilitation, whether reseals are an effective treatment depends primarily on the traffic volume and composition, and the condition of the existing pavement (including strength, cracking, and site location). Spray seals do not strengthen the pavement or correct any shape deficiencies and are unsuitable for areas subject to high shear forces such as intersections, tight corners and steep climbing lanes. They also generate too much traffic noise to be suitable for high speed roads in urban areas.

Structural overlay

Structural overlays are typically the placement of one or more layers of asphalt over the existing pavement surface. The additional layer/s can help to improve the pavements structural capacity. However this method is

unsuitable for locations where the existing profile of the road must remain unchanged or raising the entire profile of the road for a section repair will be cost prohibitive. It is also unsuitable as a rehabilitation treatment for pavement which is severely cracked.

Full Reconstruction

Reconstruction generally involves the removal and replacement of the existing pavement layers down to the subgrade, which may also require strengthening. This method is the most time consuming and costly due to lengthy construction times, traffic disruption and management, the transport and purchase of new pavement material and disposal of the removed material.

Cementitious Stabilisation

Cementitious stabilisation typically involves ripping and milling the existing asphalt and basecourse layers which becomes the road base. The surface is levelled and cement is truck spread across the pulverised road base surface, water and cement is incorporated into the road base by a milling/mixing machine then compacted. Once the required density and surface shape has been achieved the road base is surfaced with an appropriate wearing course. The main benefits of this method of pavement rehabilitation are as follows;

- This method is faster than full reconstruction.
- It can improve the structural capacity and shape of the original pavement significantly.
- It allows the original profile of the road to be retained.
- It is applicable for most pavement rehabilitation scenarios.
- It is resource and environmentally friendly as the process makes use of the existing road materials.

2.8.1 Rehabilitation Case Study

A case study conducted by Smith and Vorobieff compared the costs associated with five pavement rehabilitation strategies for a typical pavement in Western Sydney which was unable to carry traffic loads. The study was based on a project carried out by Stabilised Pavements of Australia (SPA) in 2004. The following graph (Figure 2-6) clearly shows that the environmental, social and direct costs for rehabilitation of the pavement using stabilised basecourse are significantly less than the other four options. They noted that the social costs were low across all five options as this was not a heavily trafficked project site; however they expected that the social costs for rehabilitation strategies in high traffic volume locations would be of similar significance (Smith & Vorobieff, 2007).

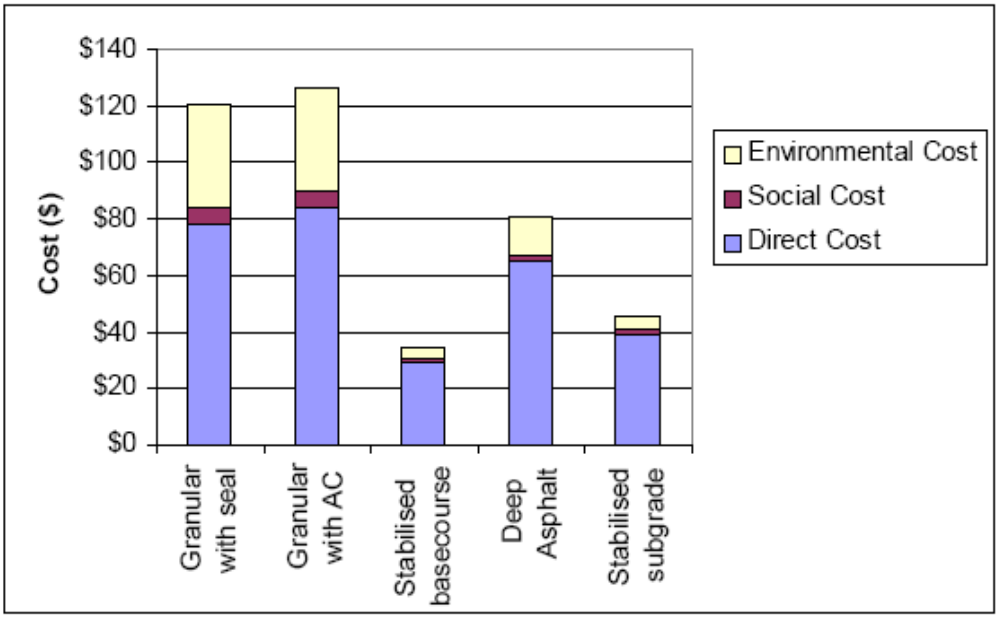

Figure 2-6: Graphical comparison of direct, social and environmental costs for example site. (Smith, 2005)

2.9 Social, Environmental and Economic Benefits

There are many advantages to be gained from pavement stabilisation. Factors such as the social, environmental and economic benefits must be taken into account when evaluating the overall advantages of utilising pavement stabilisation in both construction and rehabilitation. Triple bottom line analysis highlights the benefits inherent in the rehabilitation of existing pavement; benefits which are consistent with Australia's sustainable development goals.

2.9.1 Social

From a social perspective, there are numerous advantages to be had from pavement rehabilitation. These include:

Project Completion Times

As there is very little excavation or material export/import required by in-situ stabilisation due to the existing pavement layers being recycled, the speed at which a section of pavement can be repaired is much higher than that of other rehabilitation methods- Andrews and Dey found project completion times were generally at least 30% quicker when using in-situ stabilisation methods (Andrews & Dey, 1998).

User Impact

As full width access of the road is given at the end of each work period, traffic delays are reduced and the work site is much safer. The reduction in delays due to road closures mean less disruption to economic activity, business, personal activity, public services and emergency services (Smith & Vorobieff, 2007). The recycling of in-situ pavement materials also reduces the risk of delays caused by bad weather. Trials conducted by the Brisbane City Council found that the stabilised pavement was vulnerable to rain damage for a very short period while pavement undergoing conventional reconstruction was exposed to rain damage for most of the reconstruction time (Jones, 1996).

Road Safety

The road environment is critical to safety and is a factor in almost one-third of road crashes. The safety of the road environment can be significantly affected by maintenance and minor works and improvements (Auditor General, 2009). As the condition of the road surface is improved by the rehabilitation process, the drivability of the road and therefore the safety of the road users is increased (Austroads, 1998).

Reduced Pollution

Harmful gas emissions, noise and dust pollution around pavement construction sites are reduced due to the reduction in material haulage required for in-situ stabilisation practices (Austroads, 1998).

2.9.2 Environmental

The environmental benefits include:

Material Demands

Very little extra material is required for the in-situ stabilisation of existing granular layers, and as a consequence there is less demand on local pits and quarries. This reduction in demand for granular material also minimises the need to look for new quarry sites and therefore reduces the environmental footprint and the impact on wildlife habitats.

The reduced need for quarried material significantly diminishes the finite resource requirement of pavement rehabilitation. Having less material removed from the site lessens the loss of an asset, as the existing road base material is no longer excavated and disposed but recycled and reused to form the new pavement (Austroads, 1998).

Reduced Energy Requirements and Pollutants

There are fewer steps in the in-situ rehabilitation process; consequently the associated construction related energy usage is less.

Quarried granular materials can require energy intensive manufacturing and refinement processes, and energy is consumed in the transport of the road base material from source to pavement construction. Energy requirements are therefore significantly reduced due to the reuse of the existing material.

With the reduction in energy needed to source material and complete the pavement stabilisation, the harmful gas emissions from production plants, trucks and other equipment is therefore reduced (Austroads, 1998).

Recycling Industrial Waste and Reducing Landfill

In-situ stabilisation is able to make use of the existing road base material, industrial waste and/or by-products such as fly ash and slag. This translates to a significant reduction in volumes of waste that need to be disposed of elsewhere and therefore reduces the stress on tip and landfill sites (Wilmot & Vorobieff 1997).

Government Sustainability Agenda

Due to the growing expectation of communities in Australia that all levels of government need to be environmentally conscious, there is increasing demand by governing bodies for "new" infrastructure with minimal disruption to the existing environment. Roads are seen as a prime target for new and tighter environmental policies directed at actions towards the reduction of greenhouse gas emissions, more stringent containment requirements for existing and new quarries, and support for the sustainable use of building and construction material. Given the low impact, high serviceability nature of pavement rehabilitation, in-situ stabilisation to resurface and recycle roadways fills all the required criteria (White, 2006).

2.9.3 Economic

Simple economics show a distinct advantage in favour of pavement rehabilitation.

Direct Costs

In the majority of cases Warren Smith found that the continuous process of rehabilitation using stabilisation techniques generally result in 30% and in some cases more than 50% lower capital costs than demolition and reconstruction (Smith, 2005). When reviewing Local Government roads Hodgkinson also found that the economic performance of the recycling process is very favourable, with recycling costs generally 35-50% of the cost of full reconstruction (Hodgkinson, 1991).

Indirect Costs

As the in-situ stabilisation results in a much stiffer pavement, rutting and potholes occur less frequently, thereby reducing ongoing maintenance costs (Wilmot, 1991).

The environmental approvals process for obtaining permission for the opening up of new quarries and landfill sites can be lengthy and result in unforeseen delays to construction. The approvals process can be costly, and delays to project completion times will always result in increased overheads and expenditure.

Climatic Diversity

Having soil-cement sub-base/base in road pavements greatly increases the climatic range in which the road will perform well, reducing the need for region specific pavements and all the costs associated with their development.

Material Choices

Since the inclusion of industrial waste such as ground granulated blast furnace slag and fly ash into blended cement products, pavement designers have a greater choice for suitable materials to be included in stabilisation

projects. This means pavement materials can be sourced locally, reducing transport costs and the increased competition between primary suppliers can further cut costs (Wilmot & Vorobieff, 1997).

2.10 Rehabilitation in Western Australia

The Western Australian Road Hierarchy covers approximately 149 000 kilometres of State and Local Government roads. The State Government Authority, Main Roads Western Australia, directly manages approximately 18 000 kilometres of road and a total of 139 Local Governments manage approximately 131 000 kilometres of this network (Main Roads WA, 2010). Much of this network is in remote and sparsely populated regions and consequently has a much smaller revenue base per kilometre of road than the other Australian states (Department of Infrastructure, Transport, Regional Development and Local Government, 2009). The majority of roads in WA are constructed with low cost, local materials (gravel and limestone) and surfaced with a thin asphalt or bituminous sprayed seal. The successful use of pavement material available at low cost, located close to the proposed road works has underpinned the development Western Australia's sealed road network (Main Roads WA, 2003a).

These roads are at increased risk of structural failure because levels of planned maintenance have declined during the last decade, resurfacing by 30 per cent and rebuilding by 80 per cent. In 2006, Main Roads' modelling predicted up to 1,400 km of roads required rebuilding and estimated the cost at almost $300 million. (Auditor General, 2009).

With limited road maintenance funding and increasing heavy vehicle axle loads reducing pavement life even further; cementitious stabilisation is an ideal low-cost pavement rehabilitation technique that can improve the strength of the underlying granular material and thereby reduce the risk of structural failure.

2.10.1 Current Practice

For cement stabilisation the most common binder type adopted in Western Australia is the addition of Low Heat (LH) cement; however General Purpose (GP) and General Blend (GB) alone or blended with slag, fly-ash or lime is also used to improve the performance of the basecourse material. Cement addition to achieve a modified pavement is typically due to the rutting and cracking problems associated with thin bound pavements. In their specification notes MRWA stipulates that typical values of 1.0%, 1.5% or 2% cement by dry mass of the granular basecourse material to achieve a 7-day Unconfined Compressive Strength (UCS) in the range of 0.6 – 1.0MPa be added to produce a modified rather than a bound pavement (Main Roads WA, 2011).

2.11 Existing Cement Content Test Methods

MRWA specifies process control to manage the method of adding cement to gravel or crushed rock base (CRB), whether it is mixed at a batching plant or spread on the road and mixed in situ. For CRB Main Roads requires that the hydrated cement treated crushed rock base (HCTCRB) is produced by blending 2.0 ± 0.1% by mass of cement with CRB and must comply with a 7 day UCS in the range of 0.6MPa – 1.0MPa (Main Roads WA, 2003b).

For other basecourse materials the cement content required is determined by the unconfined compressive strength (UCS) of the material specification. Main Roads recommends typical cement content values of 1.0%, 1.5% or 2% by dry mass of the basecourse material (Main Roads WA, 2009).

The ability to use performance-based specifications in road stabilisation contracts is limited by the known variability of the existing material and the high cost of some test procedures to measure known characteristics of the pavement material (Vorobieff, 1998). The current methods typically adopted and limitations are outlined as follows;

Unconfined Compressive Strength

When adopting in-situ stabilisation techniques it is hard to get consistent results when using the UCS of the improved materials to determine future performance. The Plasticity Index (PI) and particle size distribution of the improved material tends to vary across the pavement, and incorporated existing pavement material make testing of representative samples difficult (Paige-Green, 2008).

During contractual road construction projects testing of the UCS of the road base materials as a means to meet performance based specifications is not feasible. The method requires the representative samples to be cured for 7 and 28 day periods which would mean suspending or slowing down construction while awaiting results. Road construction projects are costly; invariably weather dependent and indirect costs such as road closure and traffic management are significant, often making delays of this nature economically prohibitive.

Contractual Test Methods

For contractual road construction projects the methods currently adopted for determining cement content during road construction include; density testing, stabilised layer thickness, geometrical limits and application rate (Crase, 1998).

The application rate is usually calculated by either of the following methods.

- Mat or Tray System.

Mats or trays with a plan area of not less than 1 m^2 are placed in the path of the spreading vehicle. The average spreading rate of cementitious material distributed over the pavement surface is calculated based on the mass of material deposited on the mat or tray.

- Continuous Weighing System.

The spreader vehicle is fitted with a fully calibrated electronic weigh scale system capable of continuously measuring and recording the mass of cementitious material spread over the pavement surface.

As Vorobieff has noted however; these performance-based specifications are limited by the variability of the existing material (Vorobieff, 1998); and the veracity of contractual test methods is reliant on the binder being evenly distributed throughout the stabilised material.

Laboratory Testing

Independent laboratory testing conducted by a commercial chemical and materials laboratory can be used to determine the cement content; however the costs and delays associated with this avenue make the development of in-house testing more viable.

- EDTA Titration & Total Calcium

Queensland Department of Main Roads, Pavement and Materials Branch specify two methods for determination of cement content. One of the methods is based on a British Standards test and uses EDTA titration to determine the cement content and the other developed in- house uses the total calcium content of the material to establish cement content (Q116A & Q116C, 1996).

- Heat of Neutralisation

Another method used by Northern Territory Road Projects Division (NTRPD) and the Road Transport Authority (RTA) NSW is the Heat of Neutralisation method. This method is based on the measurement of the heat of neutralization of the cement (NTTM 204.1).

2.11.1 MRWA In-house Testing

MRWA has commenced the development of an in-house procedure to determine the percentage of GP cement added to road base material used in construction,

rehabilitation and maintenance. The decision to develop their own method was due to the unsuitability of those methods currently available (Keeley, 2008).

The EDTA Titration & Total Calcium methods used by Queensland Department of Main Roads were considered too time consuming and complicated to suit the requirement for a quick, simple test. MRWA conducted trials using the Heat of Neutralisation method; however the trials did not produce consistent results and, as the method is only suitable for freshly mixed concrete, it lacked the scope required.

Main Roads WA decided instead to develop an in-house test method and trials of this test method were conducted in 2009 on three basecourse materials typically used in the Perth metropolitan area. The experimental results obtained for the three differing parent material samples indicated that the method was reliable within an error margin of less than 0.2% (Adamson, 2009). Due to the positive results Main Roads WA have supported continued research based on these methods.

The development on an accurate method for determining the cement content of stabilised road base material post construction has excited much interest amongst the West Australian road construction industry as this characteristic of stabilisation has been very difficult to measure, and is therefore open to dispute.

Testing of the stabilised road base material is very important for predicting the future performance of the pavement, whether they are building new roads or upgrading the existing pavement. It is also an important diagnostic tool which can be used for testing of stabilised road base pavement material during maintenance and repair to help ascertain the cause of failure.

3. METHODOLOGY

3.1 Overview of Test Procedure

The following methodology will be used to determine the cement content of the modified road base samples.

The hydrated cement modified soil sample containing a known quantity of cement is placed in a 600mL beaker with a known percentage of cement. A specific volume of known molar concentration of Hydrochloric Acid (HCL) is added to the soil sample. The test portion is agitated and an initial pH reading taken. A specific volume of known molar concentration of Sodium Hydroxide (NaOH) is then titrated into the resultant solution until pH neutral is achieved to determine the amount of HCL has been consumed. The test is repeated with increments in cement quantity (0%, 1%, 2% & 3%) and the results graphed. From this information a curve profile (of pH against NaOH volume) for the soil sample is produced which is then used to determine the mean quantity of HCl consumed for each percentage cement addition. The mean quantity of HCl consumed is then graphed against the increments in cement quantity. The resulting linear relationship between these two variables is subsequently used to verify the amount of cement present in the cement modified soil sample is the same as specified.

The procedure as outlined will typically be used to test for cement content in in-situ road base material after hydration has occurred.

3.2 Test Regimes

3.2.1 Determine any limitations of test method

Testing was conducted on crushed limestone and high PI road base material to determine suitability of method for testing of cement content in more extreme road base materials.

3.2.2 Establish long term veracity of test method

Testing was conducted on four representative basecourse materials from across Western Australia at 1, 3, 6, and 12 month hydration periods to determine validity of test method over time.

3.2.3 Material Tested

The following basecourse and sub-base quality materials were used for all testing:

- Crushed Rock Base (CRB), Sample Number #09M276 – New Perth/Bunbury Highway Trial Section – basecourse, sections 2 & 3.
- Pilbara Scree gravel, Sample Number #10M57 – SLK 1512.5 LHS 3700 m Great Northern Highway H006.
- Mid-West Lateritic Gravel, Sample Number #08G192 – Geraldton Southern Transport Corridor (GSCT) Stage 2.
- Wheatbelt North High PI Lateritic Gravel, Sample Number #09M276 Northam.
- Limestone, Sample Number # 09M153 – New Perth/Bunbury Highway Sub-base trial sections.
- Limestone, Sample Number # 09M262 – WA Limestone Quarry, Postans Rd, Hope Valley. Limestone for bitumen stabilised limestone (BSL) product.

Figure 3-1: Crushed Rock Base (CRB).

Figure 3-2: Pilbara Scree gravel.

Figure 3-3: Mid-West Lateritic Gravel.

Figure 3-4: Wheatbelt North High PI Lateritic Gravel

Figure 3-5: Limestone, New Perth/Bunbury Highway Sub-base.

Figure 3-6: Limestone, WA Limestone Quarry.

3.3 Sample Preparation Equipment

Apparatus:

Convection Oven to maintain 105 – 110° C and complying with AS1289.0

Oven Trays

Sieve nest (13.2mm, 9.5mm, 4.75mm, 2.36mm, and passing 2.36mm) complying with AS1152

Test sieve shaker

Balance capable of reading to at least 0. 1g and with a limit of performance within the range of ± 0.5g

Sample trays/containers

Cement mixer

Concrete test cylinder mould and compaction disc

Compaction Hammer

Figure 3-7: Concrete test cylinder mould and compaction disc

3.4 Sample Preparation

The process described below was used to prepare all samples for testing. This method was adopted to help replicate the in-situ conditions and to facilitate the production and storage of over 400 individual samples.

Sample size

The 200 gram sample size was determined to be the minimum representative of the bulk road base materials being tested. The sample size was manageable in terms of sample handling and the scope of the testing procedure; larger samples sizes would have meant an increase in reagent and cement usage. Optimal usage of reagent and cement was balanced by the quantity of cement required for 3% addition to the sample and corresponding acid strength and volume essential to ensure that all of the cement was consumed.

3.4.1 Sample Preparation in Cylinder Mould

1. Obtain a test sample taken in accordance with test Method WA 100.1.
2. Obtain a test portion of approximately 15 kg from the test sample that has been prepared in accordance with Test Method WA 105.1.
3. Dry the test portion to constant mass (at least 24 hours) in an oven at a temperature within the range of 105^{o}C to 110^{o}C.
4. Sieve or ring mill the test portion until all material passes a 2.36 mm sieve.
5. Separate into 4 - 7 kg lots and add required cement to sample (2.5%).
6. Blend cement and sample by hand until uniform distribution then either add blended sample to electric mixer or continue to hand mix.
7. Hydrate with 6 - 10% water and mix thoroughly for 10 minutes.
8. Using circular compaction disc (for concrete test cylinder mould) as template cut number of required circles from heavy duty plastic to act as separators.
9. Prepare concrete test cylinder mould by coating with de-bonding oil and place separator circle at base of cylinder mould.
10. Weight out sample into ~ 200 gm lots.
11. Place 210 gm of prepared sample into mould.
12. Place separator circle then compaction disc on top of sample and compact.

13. Continue with this process until the cylinder is full (approximately 14-15 samples).

Figure 3-8: Sample in cylinder mould sample

Figure 3-9: Compacting

14. Place cylinder in moist environment and let cure overnight.
15. Remove samples from cylinder without separating the layers, double wrap securely in plastic wrap and place into a suitable container for the remainder of the required hydration period.

Figure 3-10: Removing sample from mould

Figure 3-11: Samples prepared for hydration

Figure 3-12: Sample storage during hydration period

3.5 Test Equipment

Figure 3-13: Equipment set up in fume cupboard

Test Apparatus:

Balance capable of reading to at least 0.01g and with a limit of performance within the range of ± 0.05g

Glass beakers: one 1000mL, two 600ml and three 200ml beakers

Volumetric flasks, two 1000mL flasks with stoppers for storage of reagents

Stirring Rod

Glass Funnel 100mm Diameter

Retort Stand

Burette, one 50mL burette graduated in 0.1mL divisions

Pipette, one 50mL bulb pipette

Pipette filler

Measuring cylinder, one 1000mL graduated cylinder

Distilled Water

Wash bottle

pH meter

Equipment Handling

The pH meter requires calibration before commencing testing to ensure an accurate pH reading and to verify that the pH meter is reliable and can maintain reading accuracy.

The pH meters are very sensitive and easily damaged so care should be taken to remove them from the beaker during agitation of the sample throughout testing.

The burette used for the titration of the NaOH solution should be rinsed out at the end of each testing session to prevent "freezing" of the stopcock.

Figure 3-14: Recording pH reading of test sample

3.6 Test Reagents

3.6.1 Sodium Hydroxide

Sodium Hydroxide Pellets (M.W. 40.00)

1 Add 280 gm of Sodium hydroxide (NaOH) pellets to a 1000ml beaker.

2 Add approximately 600ml of distilled water and stir until pellets are dissolved.

3 Pour contents into a stoppered 1000ml volumetric flask and dilute solution to 1000ml with distilled water.

3.6.2 Hydrochloric Acid

Hydrochloric Acid Solution (32%)

1 Add 700ml concentrated hydrochloric acid to a 1000ml measuring cylinder.

2 Make up to 1000ml with distilled water.

3 Transfer contents to a stoppered 1000ml volumetric flask.

Reagent Concentration

The concentration of the regents was chosen based on the strength of Hydrochloric Acid required to dissolve all of the cement in the samples while keeping the quantity used to a minimum to avoid waste. It was also necessary to use at least 50ml of HCL to ensure a minimum volume of 25ml of NaOH was titrated through the burette for all tests. This helped reduce the level of error and uncertainty associated with burette and pipette usage and ensured the error margin was not too high.

3.6.3 Test conditions - Safety

Concentrated hydrochloric acid (fuming hydrochloric acid) forms acidic mists. Both the mist and the solution have a corrosive effect on human tissue, with the potential to damage respiratory organs, eyes, skin, and intestines. Solutions of sodium hydroxide will cause chemical burns, permanent injury or scarring, and blindness if it contacts unprotected human or animal tissue.

Protective equipment (PPE) such as rubber gloves, safety clothing and eye protection should always be used when handling the material or solutions.

Due to the highly acidic (HCl) and highly caustic (NaOH) nature of the reagents used in the testing procedure all testing should be conducted in a fume cupboard to prevent inhalation of toxic fumes.

Reagents Handling

Before handling the solutions the operator must consult the relevant Material Safety Data Sheets (MSDS) for safe handling and storage.

The 7M sodium hydroxide solution must be protected from carbon dioxide in the air as the carbon dioxide reacts with the sodium hydroxide; the sodium hydroxide is also hygroscopic and readily absorbs water from the air. Both can changes its concentration so it must be stored in an airtight container. The sodium hydroxide solution has only a short shelf life so only the required amount of solution should be made up for testing.

The 7M Hydrochloric Acid solution can be made up and stored for the duration of the testing in an airtight container.

Avoid contamination of the prepared solutions by using clean equipment and by never returning any unused portion of solution to the storage container.

Solutions should not be stored for long periods in the volumetric flasks as evaporation may cause the stopper to “freeze” into the top of the flask.

3.7 Test Procedure

Once hydration period is complete remove sample/s from the gladwrap.

1 Place the hydrated sample in a suitable container and using a pestle break sample down.
2 Place sample into 600ml beaker and weigh and record weight. Ensure all samples are very similar in weight ~200 gm.
3 Add required cement (0%, 1%, 2% & 3%) according to mass.
4 Pipette 50ml of prepared HCl solution into sample container, mix thoroughly to ensure cement and gravel is combined with the acid then leave for 5 minutes.
5 Stir contents thoroughly and then add 100ml distilled water, washing down the stirrer, do not mix further.
6 Cover and let stand ~8 hrs or overnight.
7 Stir contents thoroughly after interval.
8 Into burette measure 50ml of prepared Sodium Hydroxide solution.
9 Titrate the following quantities of NaOH into beaker, agitate mixture thoroughly with stirring rod and record pH when mixture stabilises. These quantities will ensure a starting pH of ~2 which will help prolong the life of the pH meter.
    1. 20 mL for 0% cement addition
    2. 15 mL for 1% cement addition
    3. 10 mL for 2% cement addition
    4. 5 mL for 3% cement addition
10 Continue addition of NaOH into beaker in 1 to 5 mL increments, agitate mixture thoroughly with stirring rod and record pH when mixture stabilises.
11 Continue addition of NaOH until pH range 7- 8 is achieved before discarding mixture.

The test procedure is repeated 3 times to get representative results for each cement percentage addition.

4. EXPERIMENTAL RESULTS

4.1 Determine limitations of test method

Testing was conducted on Limestone, Sample Number # 09M153, Limestone, Sample Number # 09M262 and Wheatbelt North High PI Lateritic Gravel, Sample Number #09M276 to determine suitability of method for testing of cement content in Western Australia's more extreme road base materials. All samples were prepared and tested according to the outlined sample preparation and test procedure covered in Chapter 4: Methodology. All samples were hydrated for a period of one month prior to testing. All test results for these materials are included in Appendix A.

4.1.1 Testing issues and outcomes for Limestone, Sample # 09M153

Samples 1 – 4

Testing was conducted initially as per the outlined procedure where 50mL of 7Molar Hydrochloric acid (HCl) was added to the 200gm samples. The acid reacted very strongly with the parent material. Once all signs of reaction had ceased 100mL of distilled water was added and the pH of the first sample was taken. The pH reading was 7.34↑indicating that no acid was left in the sample. 150mL of HCl was subsequently added in 50mL increments bringing the pH to 3.46↑. From these results it was considered necessary to remove the addition of 100mL of distilled water.

Sample 5

The test was conducted without the addition of the distilled water. 350mL of HCl was added in 50mL increments to achieve a starting pH of 0.57. Approximately 5.8 mL of NaOH was then titrated into the sample to achieve pH 7. However the amount of NaOH used was considered too low; considering the decrease in NaOH evident with the increase in cement content during previous testing, and the error margins associated with burette usage.

Sample 6

400 mL of acid was added in 50mL increments to achieve a starting pH of less than 0.00 and pH neutral occurred at 9mL of NaOH. Again this was considered too low for the same reasons as for sample 5 and the amount of acid used unwarranted.

The test procedure was then modified again to reflect the highly reactive nature of the parent material. The sample size was reduced to approximately 100 gm, the HCl strength was increased to 10 Molar and the NaOH strength reduced to 2 Molar.

Sample 7

The test was conducted after the addition of 200mL of HCl; with pH 7 occurring after approximately 18.5 mL of NaOH had been titrated into the sample.

Sample 8

The test was conducted after the addition of 150mL of HCl; with pH 7 occurring after approximately 18.0 mL of NaOH had been titrated into the sample.

The results from the testing for samples 7 and 8 indicated that the test modifications were satisfactory. In the previous test regimes the usage of NaOH was lowest when the 3% cement was added to the hydrate sample, so further tests where conducted with 3% cement addition to determine the value of NaOH consumed

4.1.2 Testing issues and outcomes for Limestone, Sample # 09M262

Samples 9 – 16 were tested with 3% cement addition and samples 17 - 19 were tested with 2% cement addition. All samples were ~ 100 gm, with the following reagent quantity and concentration; 150mL HCl 10 Molar and 50 mL 2 Molar NaOH.

The results of testing are shown in Table 4-1, and the results from the titrations were graphed as per Figure 4-1.

Table 4-1: Outcomes of testing for 2% and 3% cement addition.

Sample Number	Cement addition	Outcome
9	3%	beaker overflow
10	3%	pH neutral achieved at ~ 21.0 mL
11	3%	pH 8.43 at 6.0 mL, erratic readings Changed battery on pH meter
12	3%	pH neutral achieved at ~ 21.5 mL
13	3%	pH neutral achieved at ~ 27.0 mL
14	3%	pH neutral achieved at ~ 17.3 mL
15	3%	pH neutral achieved at ~ 21.0 mL
16	3%	pH neutral achieved at ~ 21.5 mL
17	2%	pH neutral achieved at ~ 19.5 mL
18	2%	pH neutral achieved at ~ 23.0 mL
19	2%	pH neutral achieved at ~ 21.5 mL

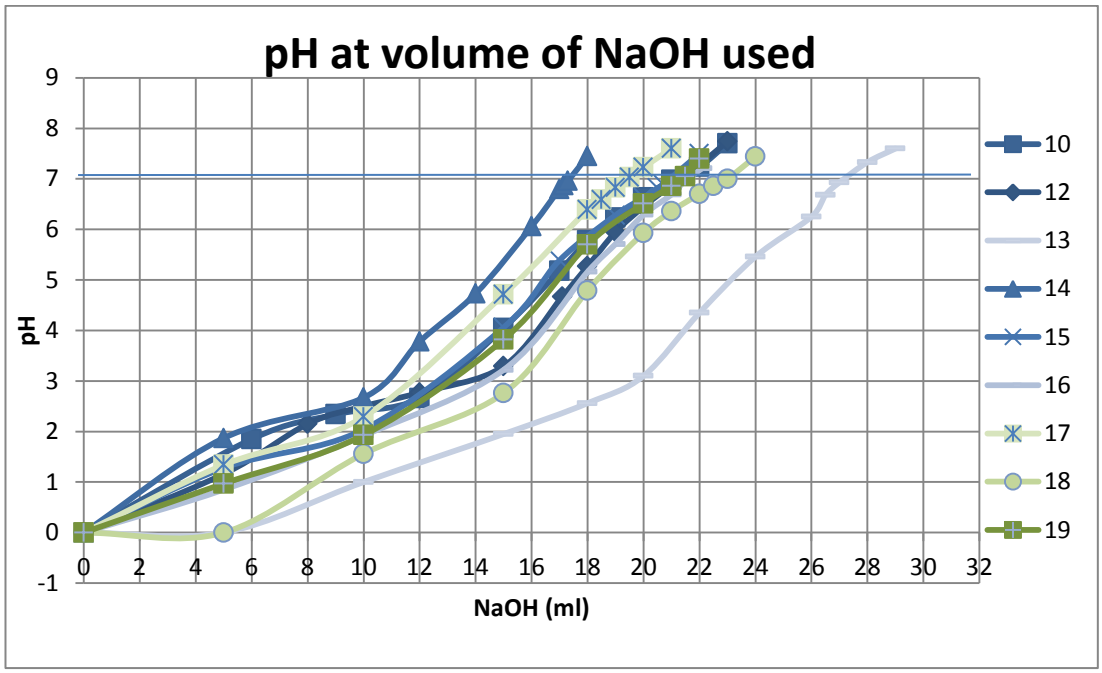

Figure 4-1: Results for NaOH addition in Limestone, Sample # 09M262 for calculation of pH neutral.

The mean values taken from the graph were then used to determine the average amount of HCl consumed for the cement content percentages and can be seen in Table 4-2.

Table 4-2: HCl consumed for 2% and 3% cement addition based on NaOH titrated for pH 7.

Sample Number	Cement Addition	NaOH used	Mean	HCl consumed
10	3%	21		
12	3%	21.2		
13	3%	27		
14	3%	17.3		
15	3%	21.00		
16	3%	21.5	21.5	128.50
17	3%	19.4		
18	2%	23		
19	2%	21.4	21.3	128.73

Table 4-2 shows the values of HCl consumed for the 2% and the 3% cement addition were very similar. This was undesirable so further testing was not considered viable using the test method as outlined.

4.1.3 Establish parameters for limestone (Calcium Carbonate) testing

To determine the limitations of the test method on materials with high calcium carbonate content such as limestone, tests were conducted with non-reactive silicate sand and calcium carbonate. The following procedure was used to determine the maximum ratio of calcium carbonate acceptable for test reliability. Samples were tested with the addition of calcium carbonate to non-reactive silicate sand starting at 50% calcium carbonate and 50% non-reactive silicate sand.

Where the concentration of calcium carbonate was 20% and higher the calcium carbonate reacted with the acid until the HCl was entirely consumed. This was

confirmed by measuring the pH after reaction of the HCl with the $CaCO_3$. The pH was approximately 7.40 indicating acid was no longer present in solution.

It was found that the test method was reliable with 7 Molar HCl and 10% concentration of calcium carbonate.

4.1.4 Outcomes for Wheatbelt North High PI Lateritic Gravel

The results for one month hydration period from the titrations for the addition of 0%, 1%, 2% and 3% cement to the sample were graphed as per Figure 4-2

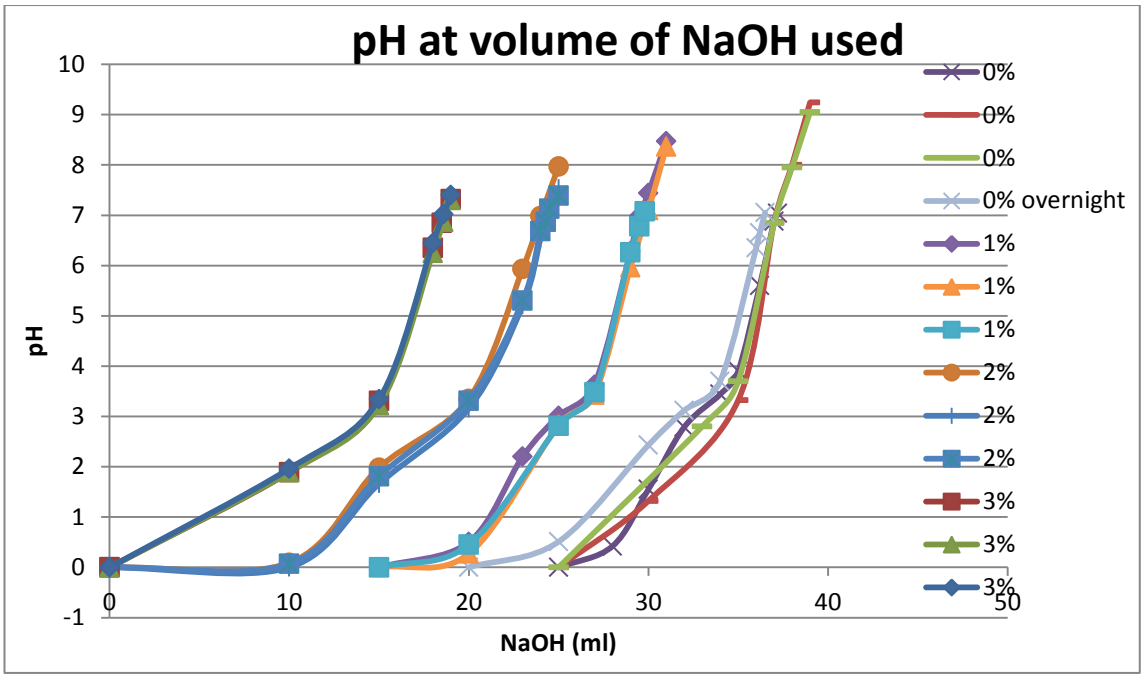

Figure 4-2: NaOH addition in High PI Lateritic Gravel at 1 month hydration

The graphed values show a distinct pattern related to the increase in cement addition and the corresponding values for pH 7 are closely aligned.

The mean values for pH 7 taken from the graph were then used to determine the average amount of Hydrochloric acid consumed and can be seen in Table 4-3.

Table 4-3: Mean consumption of NaOH (mL) and average HCl consumed

Cement Addition	Mean NaOH used	HCl consumed
0%	37.10	12.90
1%	29.77	20.23
2%	24.30	25.70
3%	18.63	31.37

This data for HCl consumed was graphed against cement addition and a trend line added to demonstrate that a linear relationship existed between the amount of cement added and the amount of HCl consumed as can be seen in Figure 4-3.

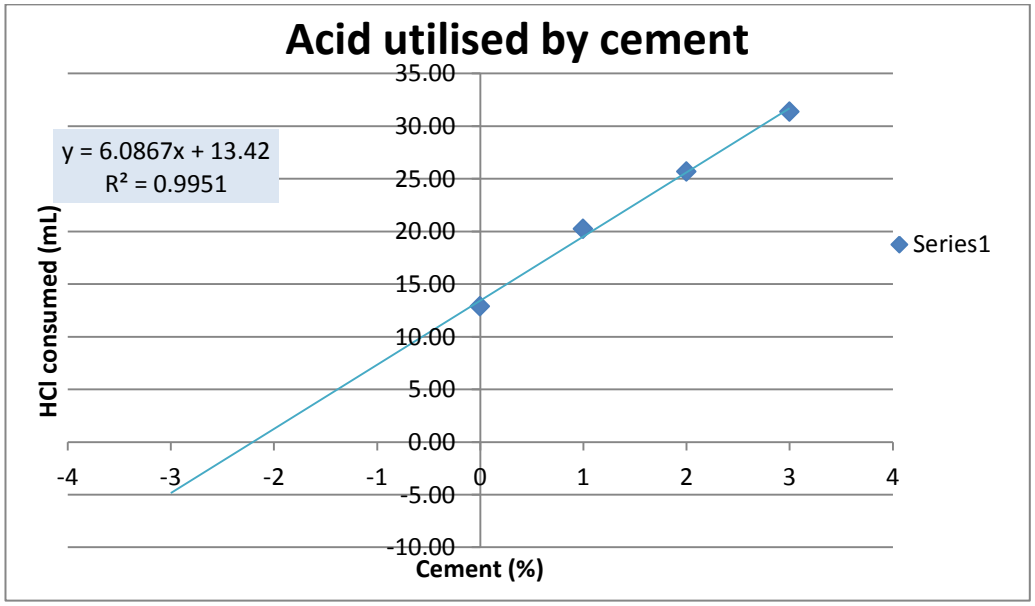

Figure 4-3: Graph of acid consumed by cement for high PI material

4.1.5 Issues

Using linear regression analysis the predicted value for original cement content of the sample was 2.20% cement addition which was within 0.3% of the actual value of 2.5% cement addition. This however does not satisfy the requirement that the test method is reliable within an error margin of ±0.2%.

This discrepancy may be attributed to samples being broken down with a pestle then tested within one hour of acid addition in contrast to the original testing procedure where the samples were left overnight before testing.

Nevertheless the results for the amount of acid consumed by the cement, shown in Figure 4-1, demonstrates a strong linear relationship and a high correlation with an R^2 value of 0.9951. This suggests the test method can successfully be used for this material.

Due to the reduced accuracy of the cement content prediction further testing was conducted. A sample for 0% cement addition was prepared with 50 mL of hydrochloric acid, left overnight and tested the following day. The retest of this sample resulted in a slight increase in the acid consumed (Table 4-4) which when plotted alongside the first result for 0% addition (see Figure 4-4) gave an R^2 value of 0.9981 and using linear regression analysis a predicted value of 2.37% cement addition.

Table 4-4: Mean consumption of NaOH (mL) and average HCl consumed for overnight sample.

Cement Addition	Mean NaOH used	HCl consumed
0%	36.40	13.60

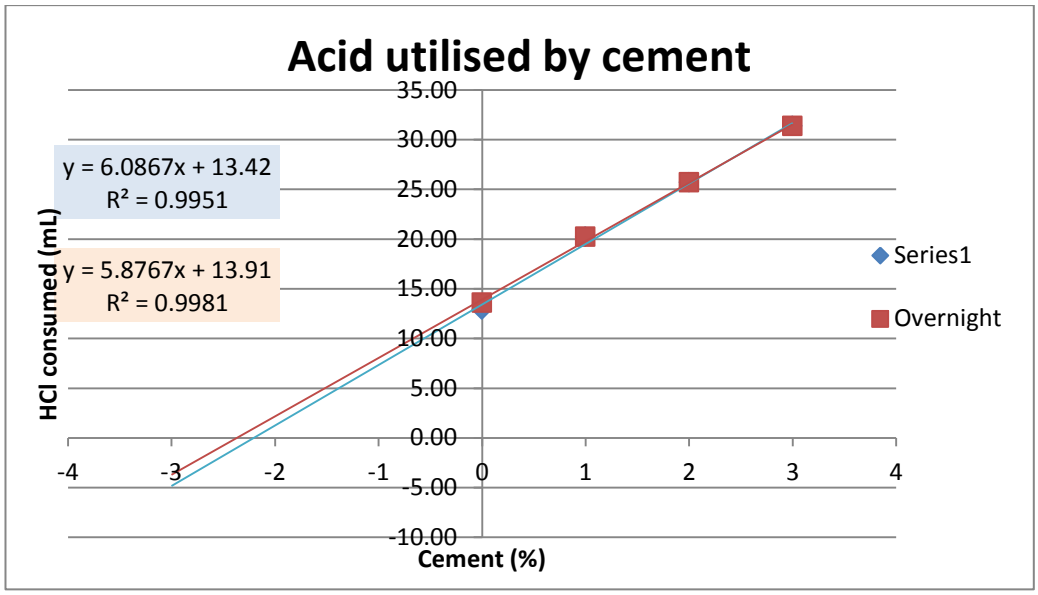

Figure 4-4: Graph of acid consumed by cement for high PI material with retested

Based on these results it was concluded that the test method was suitable for this type of material.

4.2 Discussion of limitations of test method results

The following observations were made on the suitability of method for testing of cement content for limestone and high PI material based on the results achieved from the test regime.

4.2.1 Limestone (Calcium Carbonate) testing

The initial testing of the Limestone, Sample Number # 09M153 and Limestone, Sample Number # 09M262 indicated that the test method is not suitable for this type of road base material.

The test method as outlined in the methodology is not considered suitable for testing on granular pavement material with either; a high calcium carbonate content or

granular pavement material whereby the material reacts strongly with hydrochloric acid to the extent that more than 10 % of the original mass is consumed.

The reasons are as follows;

- It was necessary to alter the molarities of the reagents and therefore the test method to accommodate the highly reactive nature of the limestone.
- Even after altering the molarities of the reagents the mean results for HCl consumption for the differing cement concentrations were not distinct enough for linear regression analysis to be applied.

4.2.2 Lateritic Gravel testing

The initial testing of the Wheatbelt North High PI Lateritic Gravel, Sample Number #09M276, high plasticity road base material indicated that the test method was suitable for this type of road base material; however an overnight delay between acid addition and testing is essential to allow the acid and cement sufficient time to react.

Testing at one month hydration will include the overnight delay before testing and the results will be analysed to confirm the suitability of the method under these parameters.

4.3 Establish long term veracity of test method

Testing was conducted on four representative basecourse materials from across Western Australia at 1, 3, 6, and 12 month hydration periods to determine validity of test method over time.

The following basecourse quality materials were used for all testing:

- Crushed Rock Base (CRB), Sample Number #09M276 – New Perth/Bunbury Highway Trial Section – basecourse, sections 2 & 3.
- Pilbara Scree gravel, Sample Number #10M57 – SLK 1512.5, Great Northern Highway, H006.
- Mid-West Lateritic Gravel, Sample Number #08G192 – Geraldton Southern Transport Corridor (GSCT) Stage 2.
- Wheatbelt North High PI Lateritic Gravel, Sample Number #09M276 Northam.

All samples were prepared and tested according to the outlined sample preparation and test procedure covered in Chapter 4: Methodology. All test results for these materials are included in Appendix A.

In order to reduce the variability created by sampling and testing of the materials the following parameters remained consistent where possible throughout the testing regime;

- Sample preparation technique
- Binder type – Cockburn GP Cement
- Binder content – 2.5% by mass
- Moisture content – 10% by mass
- Sample size – 200 gm
- Test procedure

The significant variable parameters were as follows;

- Host material
- Sample hydration period

4.3.1 Result Analysis

The variability of the test results must be reasonably low in order to gain confidence in the test method used and for reliable conclusions to be drawn about the results obtained.

The statistical analysis of all data was performed with Microsoft Office Excel and the statistical analysis techniques used throughout the investigation are briefly described in this section.

For result analysis the amount of NaOH titrated into the test sample to achieve pH 7 will be approximated from graphed results. These approximated values will be used to calculate the mean, standard deviation and Z scores using the following formula.

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i.$$

Equation 4-1: Mean

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2},$$

Equation 4-2: Sample Standard Deviation

A low standard deviation indicates that the data points tend to be very close to the mean and is an indication of the precision of the results.

The calculated standard deviation will be used to demonstrate that a reasonable correlation exists between the test sample results, which will be reflected by a low standard deviation if this correlation exists.

$$Z = \frac{\text{Result} - \bar{x}}{S}$$

Equation 4-3: Z - Score

The value of the Z score corresponds to the number of standard deviations the result is from the mean, with a negative value indicating the result is below the mean and positive above the mean.

A Z score close to zero indicates that the result is close to the other results. In their manual *Assuring the Quality of Test and Calibration Results*, Main Roads recommend that all Z scores with an absolute value of three be considered outliers, and test operations should be reviewed for results between two and three.

The Z scores will be calculated to ensure that test results with a Z score greater than two are not used for further analysis.

The following equation for small sample sizes will be used to determine the confidence interval of the sample means;

$$\overline{X}_n - A\frac{S_n}{\sqrt{n}} < \mu < \overline{X}_n + A\frac{S_n}{\sqrt{n}}$$

Equation 4-4: CI of the mean

Where $A = t_{(0.05,\, n-1)}$

and t = 2.78 for 95% when n = 5

t = 4.30 for 95% when n = 3 (taken from Table 67, Appendix B).

t = 12.7 for 95% when n = 2

Economic considerations often determine sample sizes, reliability and error targets. The confidence interval for sample sizes less than three using this procedure is disproportionately higher due to the Student t value increasing significantly with

decreasing sample size. For statistically credible results it has been concluded that a minimum sample size of three is required.

The 95% confidence interval will be determined for results with 0%, 1%, 2% and 3% cement addition. The interval estimate gives an indication of how much uncertainty there is in the estimate of the true mean. The narrower the interval, the more precise is the estimate.

The confidence interval will be calculated for the sample means of the cement percentages to ensure that the estimate of these means is reasonable and can therefore be used for the next stage of analysis.

The determination of the cement content of the tested samples was based on statistical linear regressions.

4.4 Crushed Rock Base (CRB), Sample #09M276

The results for 1, 3, 6, and 12 month hydration periods from the titrations for the addition of 0%, 1%, 2% and 3% cement to the sample were graphed as per Figure 4-5, Figure 4-6, Figure 4-7, and Figure 4-8.

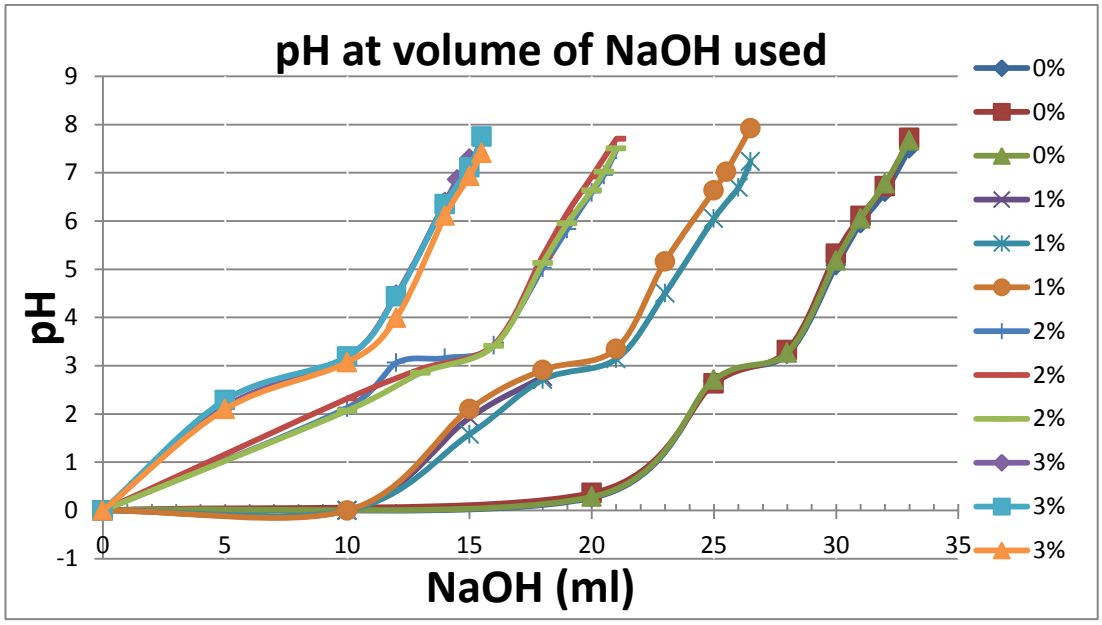

Figure 4-5: Results for NaOH addition in CRB at 1 month hydration.

Using the linear equation from the graph the predicted value for original cement content of the CRB sample for one month hydration was 3.09%. The results were much higher than expected and did not satisfy the requirement that the test method is reliable within an error margin of ±0.2%. The test procedure was therefore reviewed and the following observation was made;

- During testing Anchor brand distilled water had been used in the first half of the testing then, due to supply problems, MRWA Materials Engineering Branch (MEB) in-house laboratory produced de-ionised water was used for the second half.

Testing was repeated on a further 12 samples at one month hydration with de-ionised water to ensure that the change in testing water had not influenced the result. The result of the second testing also gave a predicted cement content of 3.09%. From this it was determined that the type of water used was not influencing test outcomes; however it is advisable that all test parameters remain consistent throughout the test procedure.

The results of the testing with de-ionised water on the samples hydrated for one month were used for this report so as to remain consistent with the 3, 6 and 12 month testing.

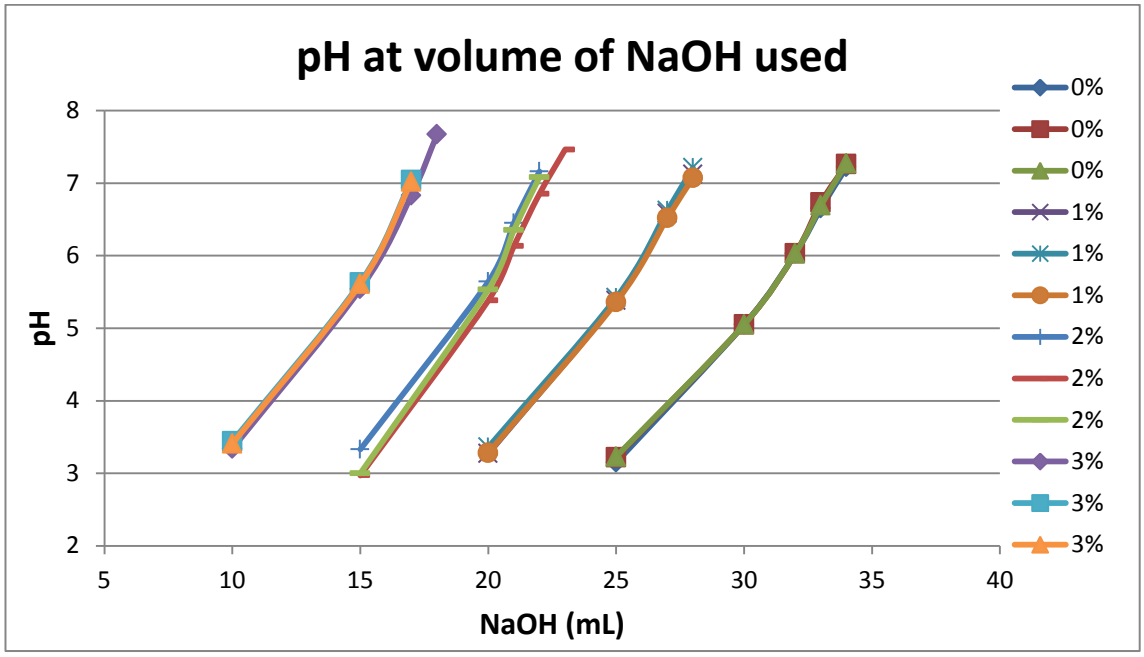

Figure 4-6: Results for NaOH addition in CRB at 3 months hydration.

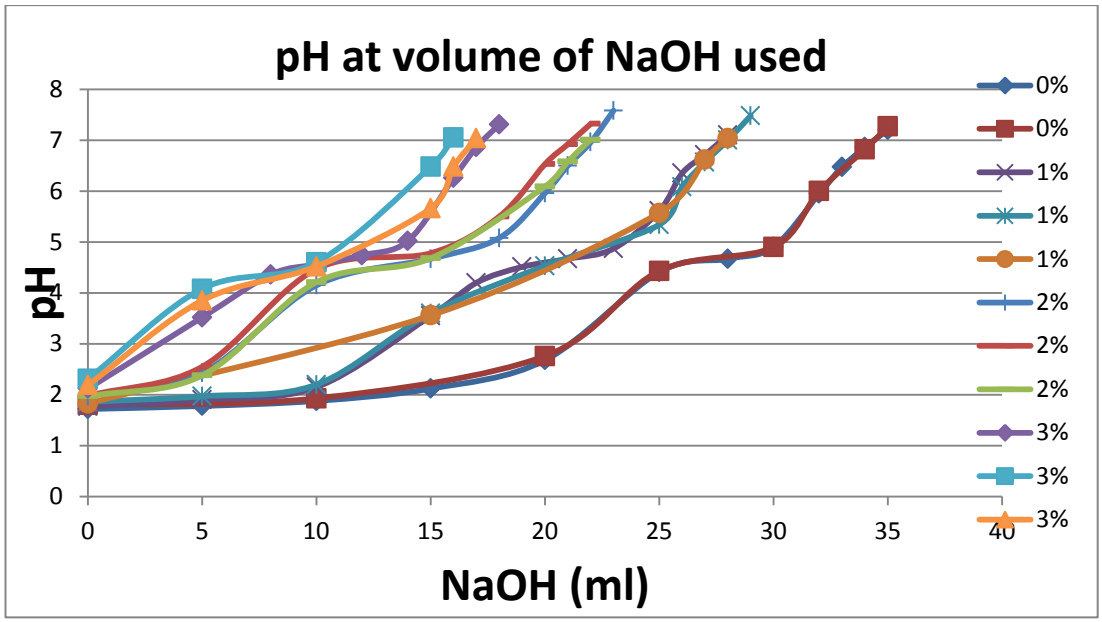

Figure 4-7: Results for NaOH addition in CRB at 6 months hydration.

The testing of the three 0% cement addition samples at 6 month hydration only considers two test results. This is due to the testing of the third sample being delayed by a period of 15 days due to problems with the pH probe and its subsequent replacement. The third test was not included as the results of the test were not thought to be reliable.

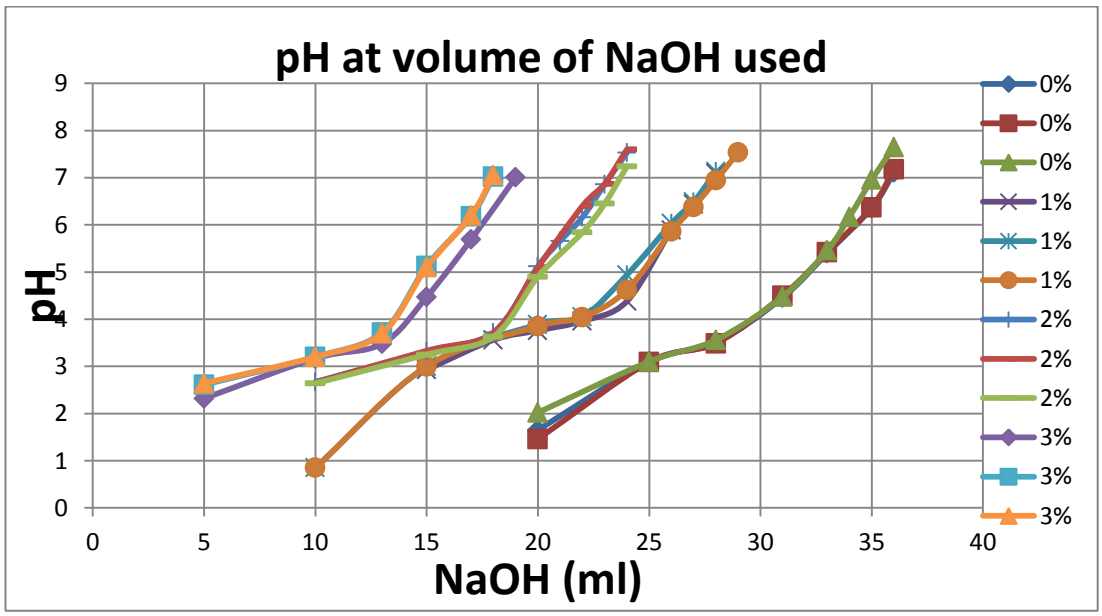

Figure 4-8: Results for NaOH addition in CRB at 12 months hydration.

4.4.1 Results Analysis of CRB Samples

The graphed values for all hydration periods show a distinct pattern related to the increase in cement addition to the test samples.

The amount of NaOH titrated into the test sample to achieve pH 7 was approximated from these graphed results. These approximated values were used to calculate the mean, standard deviation, and the confidence interval of the mean using the formula from Equation 4-1, Equation 4-2 and Equation 4-4, and are shown in Table 4-5.

Table 4-5: Mean consumption of NaOH (mL), SD and CI for CRB samples.

Hydration Period	Cement	Mean	Standard Deviation	Confidence Interval
1 month	3%	14.90	0.26	±0.66
	2%	20.37	0.23	±0.57
	1%	25.90	0.57	±1.40
	0%	32.37	0.12	±0.29
3 months	3%	17.10	0.17	±0.43
	2%	21.93	0.23	±0.57
	1%	27.87	0.06	±0.14
	0%	33.47	0.06	±0.14
6 months	3%	16.73	0.64	±1.60
	2%	21.77	0.59	±1.45
	1%	28.00	0.00	±0.00
	0%	33.60	1.39	±3.44
12 months	3%	18.33	0.58	±1.43
	2%	23.43	0.23	±0.57
	1%	27.93	0.12	±0.29
	0%	35.67	0.58	±1.43

The low standard deviations indicate a reasonable correlation exists between the test sample results.

The confidence intervals (shown in Table 4-5), calculated for the sample means suggest that the estimate of these means is reasonably precise and therefore this data can be used for further analysis.

These values were also used to calculate the Z scores using the formula from Equation 4-3, and are shown in Table 4-6.

Table 4-6: Z - scores for CRB samples.

Hydration Period	Cement	Z Score		
1 month	3%	-1.13	0.38	0.76
	2%	-1.15	0.58	0.58
	1%	0.71	-0.71	-
	0%	-0.58	-0.58	1.15
3 months	3%	-0.58	-0.58	1.15
	2%	-0.58	-0.58	1.15
	1%	0.58	-1.15	0.58
	0%	0.58	-1.15	0.58
6 months	3%	-1.14	0.41	0.73
	2%	-1.14	0.40	0.74
	1%	0.0	0.0	0.0
	0%	-1.15	0.58	0.58
12 months	3%	-0.58	-0.58	1.15
	2%	-0.58	-0.58	1.15
	1%	-1.15	0.58	0.58
	0%	0.58	0.58	-1.15

The highest Z score (shown in Table 4-6), is ±1.15 indicating that the test results for the CRB are satisfactory with none having an absolute value ≥ 2; therefore all values can be used for further analysis.

As the statistical analysis techniques indicated that the test results were reasonable, the mean values taken from the graph were then used to determine the average amount of Hydrochloric acid consumed for each cement content percentage and can be seen in Table 4-7.

Table 4-7: HCl (mL) consumed based on mean results for CRB samples.

Hydration Period	% cement	HCl (mL) consumed
1 month	3	35.10
	2	29.63
	1	24.10
	0	17.63
3 months	3	32.90
	2	28.07
	1	22.13
	0	16.53
6 months	3	33.27
	2	28.23
	1	22.00
	0	16.40
12 months	3	31.67
	2	26.57
	1	22.07
	0	14.33

This data was graphed and a trend line added to demonstrate that a linear relationship existed between the amount of cement added and the amount of HCl consumed as can be seen in Figure 4-9.

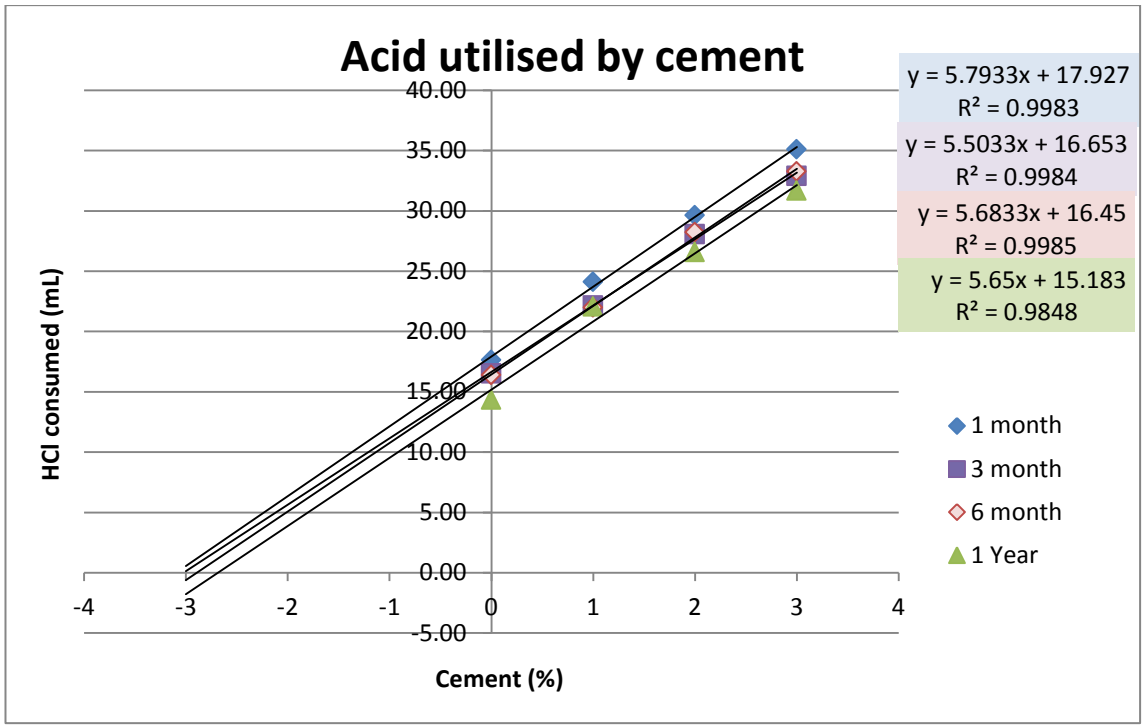

Figure 4-9: Graph of acid consumed by cement for CBR samples.

The linear trend line for the CRB samples is a very strong fit to the data with R^2 values of 0.9983, 0.9984, 0.9985, and 0.9848 confirming that a strong linear relationship does exist between the amount of cement added and the amount of HCl consumed. This relationship is significant in determining the amount of cement present in the test sample before cement addition occurred.

The linear trend line equations from Figure 4-9 were used to predict the original cement content of the samples and are shown in Table 4-8.

Table 4-8: Prediction of cement content from linear equations.

Hydration Period	Equation	Predicted cement content
1 month	y = 5.7933x + 17.927	3.09
3 months	y = 5.5033x + 16.653	3.03
6 months	y = 5.6833x + 16.45	2.89
12 months	y = 5.65x + 15.183	2.69

The actual cement addition at sample preparation was 2.5%.

The results for the Crushed Rock Base samples were not very consistent with the actual cement addition for the initial testing at one month hydration and were much higher at 3.09% than the required result of 2.5% ±0.2% tolerance. This trend continued with readings higher than 2.5% for the subsequent testing at 3, 6 and 12 months; however the incremental drop in the reading as the hydration period increased indicated that the one month testing had been accurate and that the raw CRB was somehow influencing the test results.

Further testing of the CRB will be required to determine why the results are greater than the cement addition.

4.5 Pilbara Scree gravel, Sample #10M57

The results for 1, 3, 6, and 12 month hydration periods from the titrations for the addition of 0%, 1%, 2% and 3% cement to the sample were graphed as per Figure 4-10, Figure 4-11, Figure 4-12, and Figure 4-13.

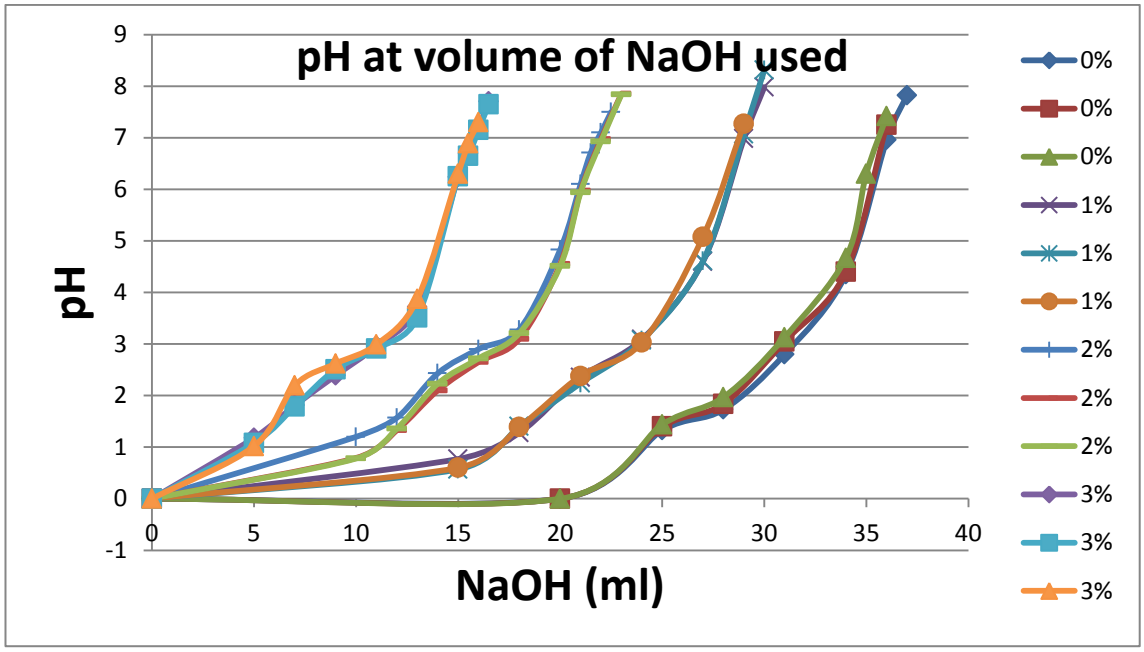

Figure 4-10: Results for Pilbara Scree Gravel at 1 month hydration.

The initial titrations for the Pilbara Scree gravel samples at 3 months hydration were flawed due to contamination of the source hydrochloric acid. Another 15 samples for this hydration period were made up as a separate batch, hydrated for 3 months and then tested at a later date. The results are shown in Figure 4-11.

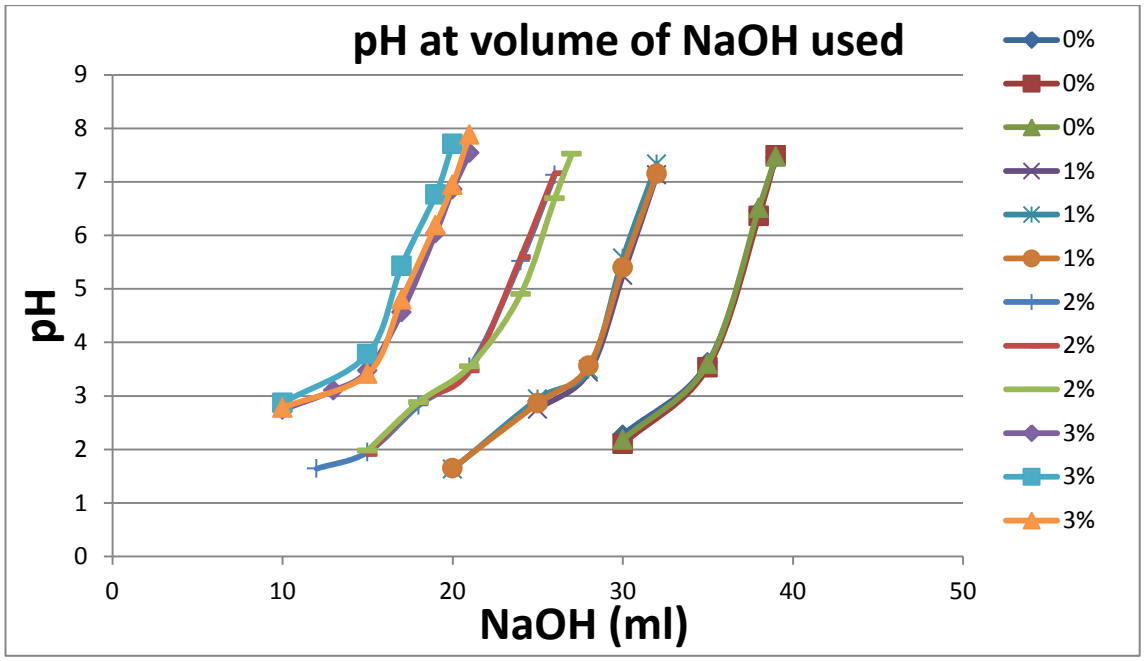

Figure 4-11: Results for Pilbara Scree Gravel at 3 months hydration.

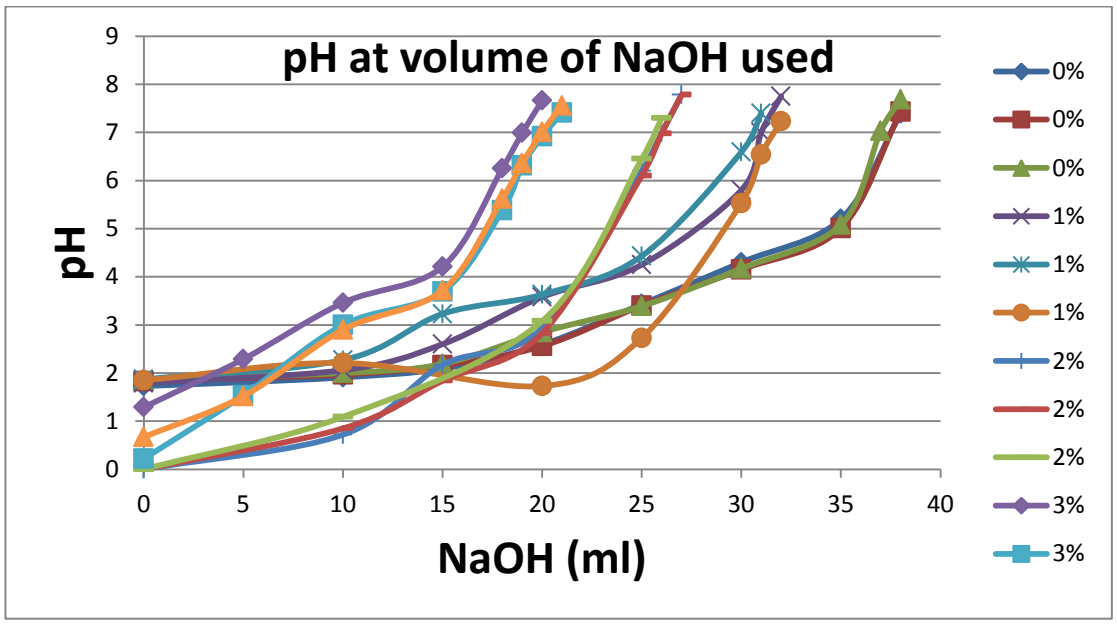

Figure 4-12: Results for Pilbara Scree Gravel at 6 months hydration.

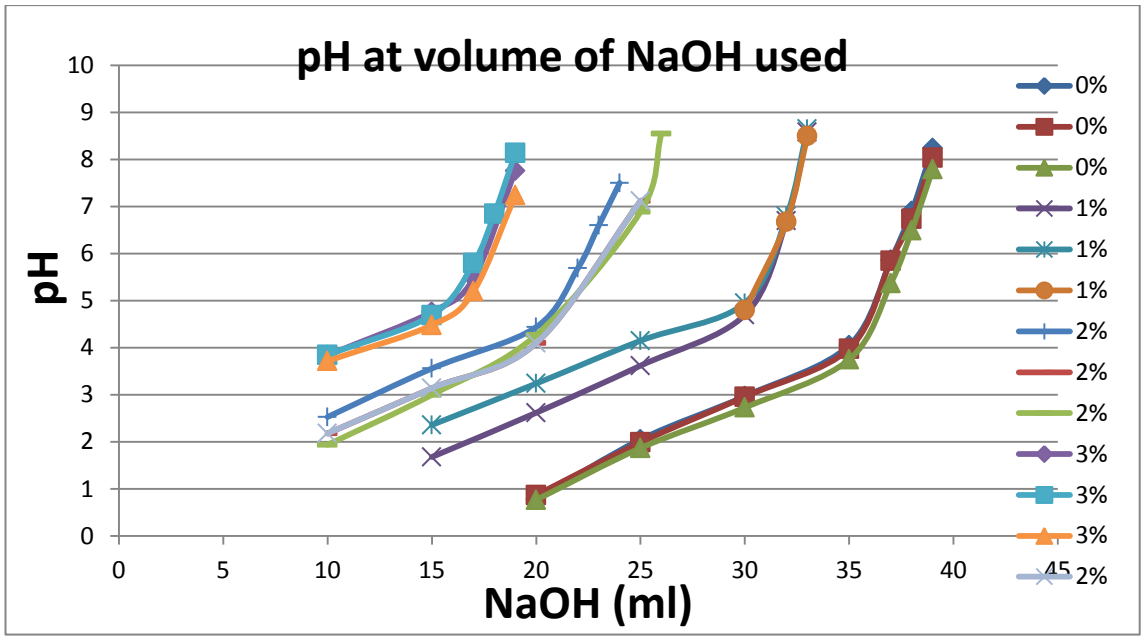

Figure 4-13: Results for Pilbara Scree Gravel at 12 months hydration.

The graphed values for all hydration periods again show a distinct pattern related to the increase in cement addition to the test samples.

4.5.1 Results Analysis of Pilbara Scree Gravel Samples

The amount of NaOH titrated into the test sample to achieve pH 7 was approximated from these graphed results. These approximated values were used to calculate the mean, standard deviation, and the confidence interval of the mean using the formula from Equation 4-1, Equation 4-2 and Equation 4-4, and are shown in Table 4-9.

Table 4-9: Mean consumption of NaOH (mL), SD and CI for Pilbara Scree Gravel samples.

Hydration Period	Cement	Mean	Standard Deviation	Confidence Interval
1 month	3%	16.00	0.00	±0.00
	2%	22.10	0.17	±0.43
	1%	28.93	0.12	±0.29
	0%	35.90	0.20	±0.50
3 months	3%	19.87	0.49	±1.22
	2%	26.00	0.35	±0.86
	1%	31.73	0.12	±0.29
	0%	38.53	0.06	±0.14
6 months	3%	19.67	0.58	±1.43
	2%	25.93	0.12	±0.29
	1%	31.13	0.61	±1.52
	0%	37.43	0.38	±0.94
12 months	3%	18.43	0.35	±0.87
	2%	25.00	0.17	±0.43
	1%	32.18	0.03	±0.07
	0%	38.17	0.21	±0.52

As can been seen from Table 4-9, the standard deviations for the Pilbara Scree Gravel samples are low and range between 0.00 and 0.61. This indicates a reasonable correlation exists between the test sample results.

The confidence intervals calculated for the sample means suggest that the estimate of these means is reasonably precise and therefore this data can be used for further analysis.

These values were also used to calculate the Z scores using the formula from Equation 4-3, and are shown in Table 4-10.

Table 4-10: Z - scores for Pilbara Scree Gravel samples.

Hydration Period	Cement	Z Score		
1 month	3%	0.0	0.0	0.0
	2%	-1.15	0.58	0.58
	1%	-1.15	0.58	0.58
	0%	-1.00	0.0	1.00
3 months	3%	0.68	0.47	-1.15
	2%	1.15	-0.58	-0.58
	1%	0.58	0.58	-1.15
	0%	1.15	-0.58	-0.58
6 months	3%	0.58	0.58	-1.15
	2%	0.58	-1.15	0.58
	1%	1.09	-0.22	-0.87
	0%	0.70	0.44	-1.14
12 months	3%	1.04	-0.09	-0.95
	2%	1.15	-0.58	-0.58
	1%	0.58	-1.15	0.58
	0%	1.12	-0.32	-0.80

The highest Z score is ±1.15 indicating that the test results for the Pilbara Scree Gravel samples are satisfactory with none having an absolute value ≥ 2; therefore all values can be used for further analysis.

As the statistical analysis techniques indicated that the test results were reasonable, the mean values taken from the graph were then used to determine the average amount of Hydrochloric acid consumed for each cement content percentage and can be seen in Table 4-11.

Table 4-11: HCl (mL) consumed based on mean results for Pilbara Scree Gravel samples.

Hydration Period	% cement	HCl (mL) consumed
1 month	3	34.00
	2	27.90
	1	21.07
	0	14.10
3 months	3	30.13
	2	24.00
	1	18.27
	0	11.47
6 months	3	30.33
	2	24.07
	1	18.87
	0	12.57
12 months	3	31.57
	2	25.00
	1	17.82
	0	11.73

This data was graphed and a trend line added to demonstrate that a linear relationship existed between the amount of cement added and the amount of HCl consumed as can be seen in Figure 4-14.

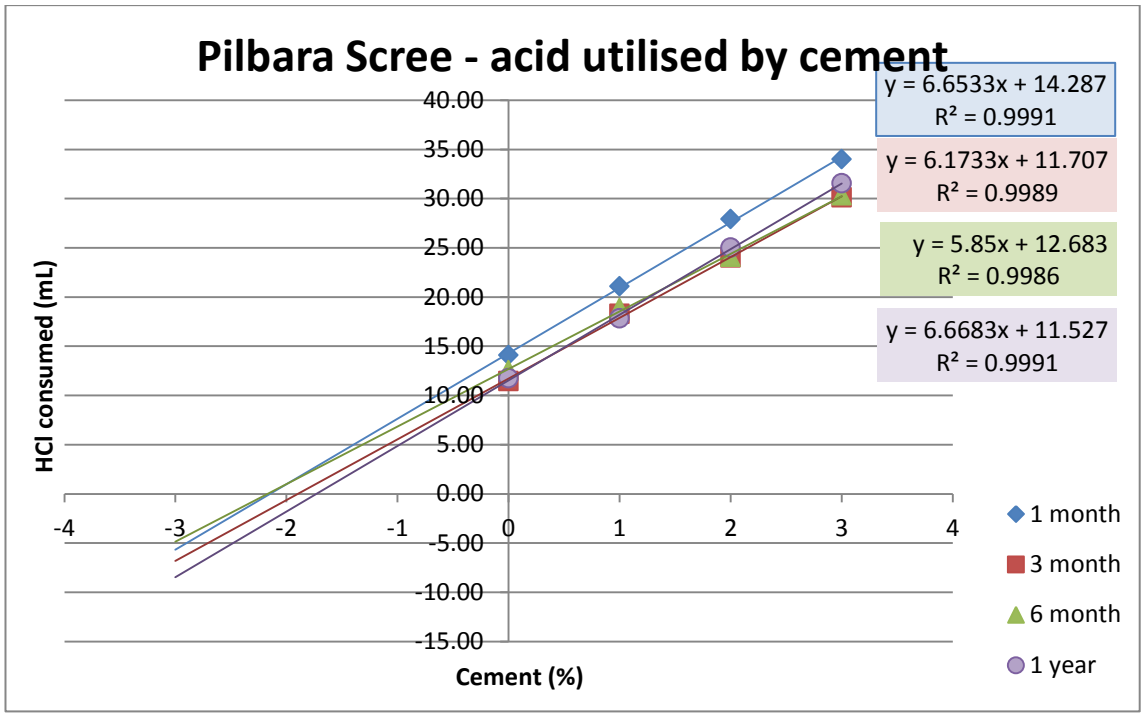

Figure 4-14: Graph of acid consumed by cement for Pilbara Scree Gravel samples.

The linear trend line for the Pilbara Scree Gravel samples is a very strong fit to the data with R^2 values of 0.9991, 0.9989, 0.9986 and 0.9991 confirming that a strong linear relationship does exist between the amount of cement added and the amount of HCl consumed. This relationship will be used to determine the amount of cement present in the test sample before cement addition occurred.

The linear trend line equations from Figure 4-14 were used to predict the original cement content of the samples and are shown in Table 4-12.

Table 4-12: Prediction of cement content from linear equations.

Hydration Period	Equation	Predicted cement content
1 month	y = 6.6533x + 14.287	2.15
3 months	y = 6.1733x + 11.707	1.90
6 months	y = 5.85x + 12.683	2.17
12 months	y = 6.6683x + 11.527	1.73

The actual cement addition at sample preparation was 2.5%

Using the linear equation from the graph the predicted value for original cement content of the sample at one month hydration was 2.15% cement addition which was within 0.35% of the actual value of 2.5% cement addition. This however does not satisfy the requirement that the test method is reliable within an error margin of ±0.2%. The subsequent testing of the Pilbara Scree Gravel samples at 3, 6 and 12 month hydration periods , although showing a very linear relationship between the amount of cement added and the amount of HCl consumed, did not showing any consistency or pattern for the prediction of cement content.

These anomalies could be in part attributed to the Pilbara Scree gravel samples at 3 months hydration being made up as a separate batch, hydrated for 3 months and then tested at a later date.

4.6 Mid-West Lateritic Gravel, Sample #08G192

The results for 1, 3, 6, and 12 month hydration periods from the titrations for the addition of 0%, 1%, 2% and 3% cement to the sample were graphed as per Figure 4-15, Figure 4-16, Figure 4-17, and Figure 4-18.

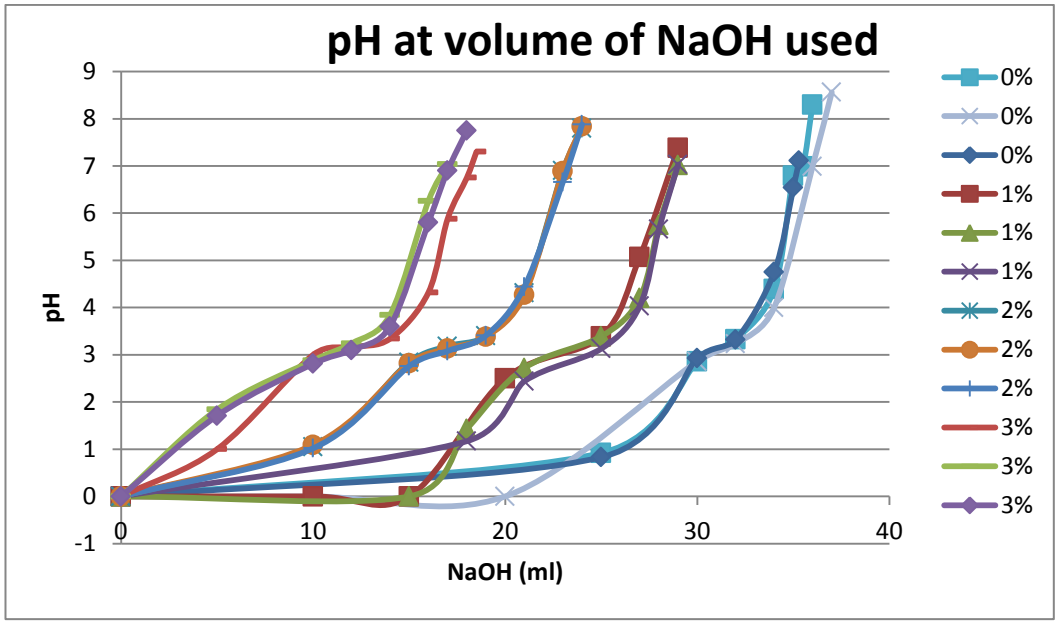

Figure 4-15: Results for Lateritic Gravel at 1 month hydration.

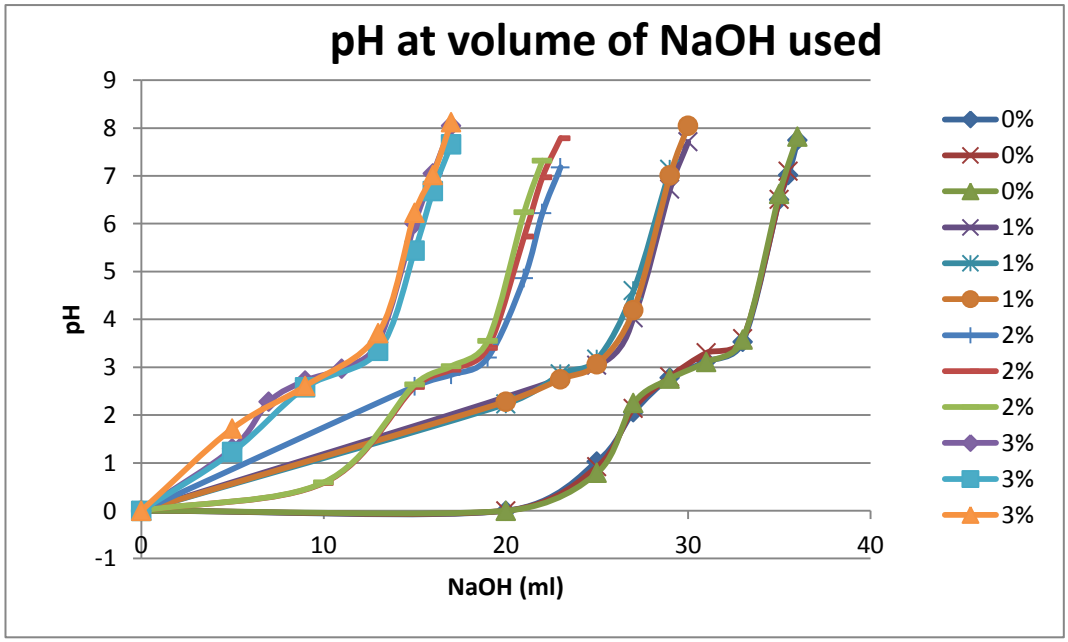

Figure 4-16: Results for Lateritic Gravel at 3 months hydration.

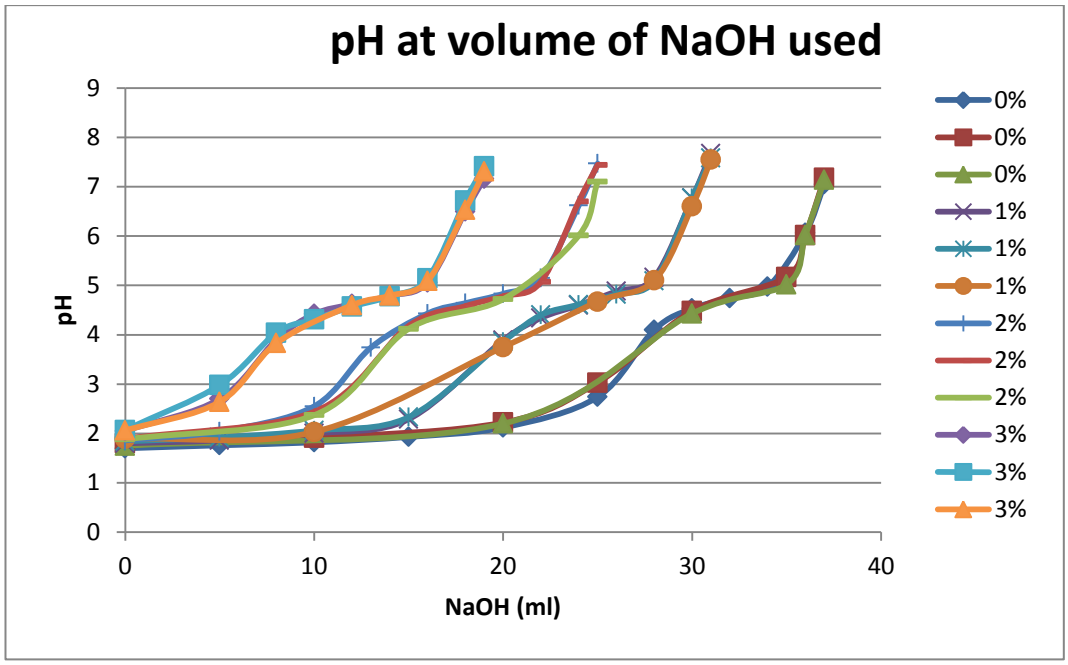

Figure 4-17: Graphed results for Lateritic Gravel at 6 months hydration.

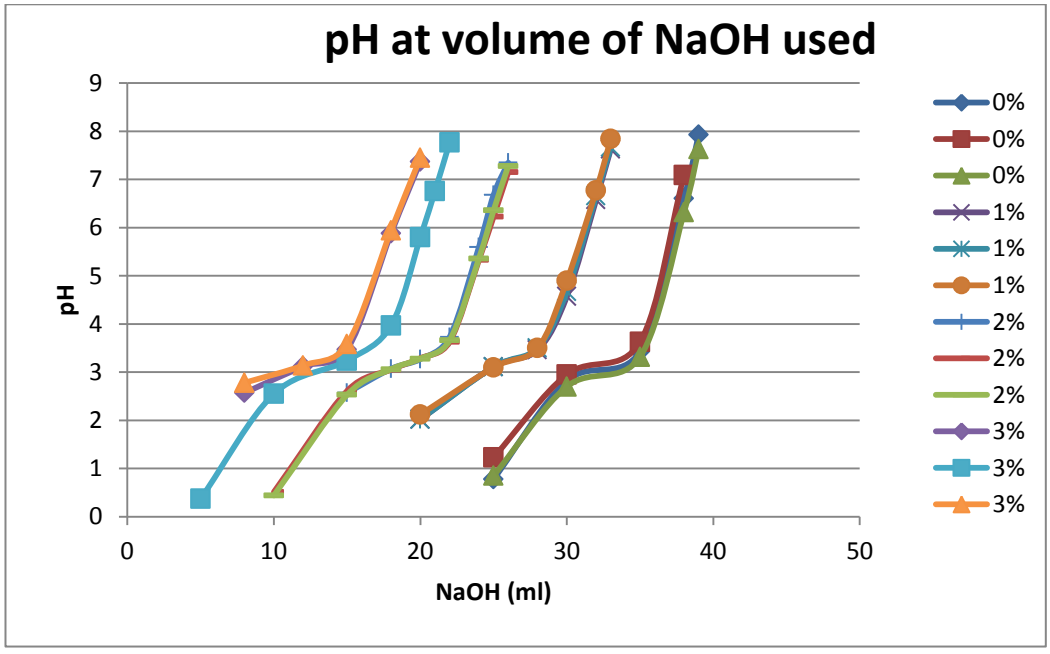

Figure 4-18: Graphed results for Lateritic Gravel at 12 months hydration.

The graphed values for all hydration periods show a distinct pattern related to the increase in cement addition to the test samples.

4.6.1 Results Analysis of Mid-West Lateritic Gravel Samples

The amount of NaOH titrated into the test sample to achieve pH 7 was approximated from these graphed results. These approximated values were used to calculate the mean, standard deviation, and the confidence interval of the mean using the formula from Equation 4-1, Equation 4-2 and Equation 4-4, and are shown Table 4-13.

Table 4-13: Mean consumption of NaOH (mL), SD and CI for Lateritic Gravel samples.

Hydration Period	Cement	Mean	Standard Deviation	Confidence Interval
1 month	3%	17.43	0.67	±1.65
	2%	23.17	0.12	±0.29
	1%	28.90	0.17	±0.43
	0%	35.58	0.38	±0.95
3 months	3%	16.10	0.17	±0.43
	2%	22.20	0.56	±1.38
	1%	29.07	0.21	±0.52
	0%	35.40	0.10	±0.25
6 months	3%	18.67	0.15	±0.38
	2%	24.67	0.21	±0.52
	1%	30.40	0.10	±0.25
	0%	37.03	0.06	±0.14
12 months	3%	20.13	1.01	±2.51
	2%	25.73	0.21	±0.52
	1%	32.47	0.15	±0.38
	0%	38.27	0.42	±1.03

As can been seen from Table 4-13, the standard deviations for the Mid West Lateritic Gravel samples are low and range between 0.06 and 1.01. This indicates a reasonable correlation exists between the test sample results.

The confidence intervals (Table 4-13), calculated for the sample means suggest that the estimate of these means is reasonably precise and therefore this data can be used for further analysis.

These values were also used to calculate the Z scores using the formula from Equation 4-3, and are shown in Table 4-14.

Table 4-14: Z - scores for Lateritic Gravel samples.

Hydration Period	Cement	Z Score		
1 month	3%	1.15	-0.50	-0.65
	2%	-0.58	-0.58	1.15
	1%	-1.15	0.58	0.58
	0%	-0.22	1.09	-0.87
3 months	3%	1.15	-0.58	-0.58
	2%	-0.90	-0.18	1.08
	1%	1.08	-0.80	-0.32
	0%	-1.00	0.00	1.00
6 months	3%	0.87	0.22	-1.09
	2%	-0.80	-0.32	1.12
	1%	1.00	0.00	-1.00
	0%	-0.58	1.15	-0.58
12 months	3%	1.15	-0.53	-0.63
	2%	0.80	0.32	-1.12
	1%	0.87	0.22	-1.09
	0%	0.80	0.32	-1.12

The highest Z score (Table 4-14), is ±1.15 indicating that the test results for the Mid West Lateritic Gravel samples are satisfactory with none having an absolute value ≥ 2; therefore all values can be used for further analysis.

The mean values taken from the graph were then used to determine the average amount of Hydrochloric acid consumed for each cement content percentage and can be seen in Table 4-15.

Table 4-15: HCl (mL) consumed based on mean results for Lateritic Gravel samples.

Hydration Period	% cement	HCl (mL) consumed
1 month	3	32.57
	2	26.83
	1	21.10
	0	14.42
3 months	3	33.90
	2	27.80
	1	20.93
	0	14.60
6 months	3	31.33
	2	25.33
	1	19.60
	0	12.97
12 months	3	29.87
	2	24.27
	1	17.53
	0	11.73

This data was graphed and a trend line added to demonstrate that a linear relationship existed between the amount of cement added and the amount of HCl consumed as can be seen in Figure 4-19.

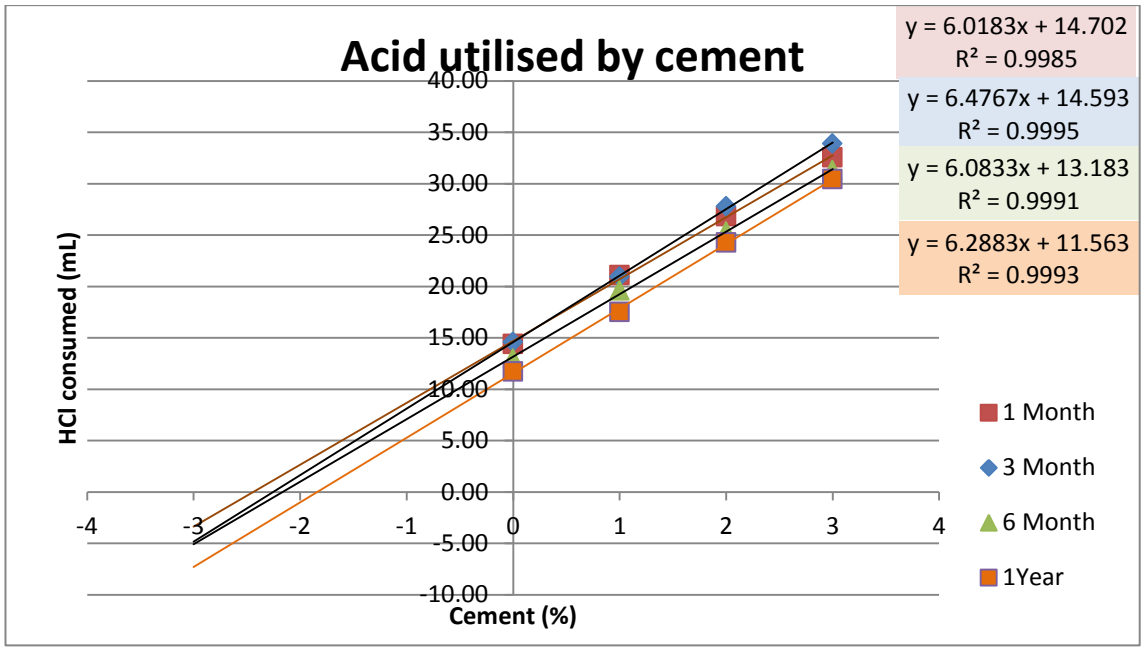

Figure 4-19: Graph of acid consumed by cement for Lateritic Gravel samples.

The linear trend line for the Midwest Lateritic Gravel samples is a very strong fit to the data with R^2 values of 0.9985, 0.9995, 0.9991 and 0.9988 confirming that a strong linear relationship does exist between the amount of cement added and the amount of HCl consumed. This relationship is significant in determining the amount of cement present in the test sample before cement addition occurred.

The linear trend line equations from Figure 4-19 were used to predict the original cement content of the samples and are shown in Table 4-16.

Table 4-16: Prediction of cement content from linear equations.

Hydration Period	Equation	Predicted cement content
1 month	y = 6.0183x + 14.702	2.44
3 months	y = 6.4767x + 14.593	2.25
6 months	y = 6.0833x + 13.183	2.17
12 months	y = 6.1133x + 11.68	1.91

The actual cement addition at sample preparation was 2.5%.

The results for the Midwest Lateritic Gravel samples at one month hydration were reasonably consistent with the cement addition for the initial testing and satisfy the requirement that the test method is reliable within an error margin of ±0.2%. However the results of the testing then show a gradual decrease in the predicted cement content with subsequent testing at 3, 6 and 12 months.

4.7 Wheatbelt North High PI Gravel, Sample #09M276

The results for 1, 3, 6, and 12 month hydration periods from the titrations for the addition of 0%, 1%, 2% and 3% cement to the sample were graphed as per Figure 4-20, Figure 4-21, Figure 4-22, and Figure 4-23.

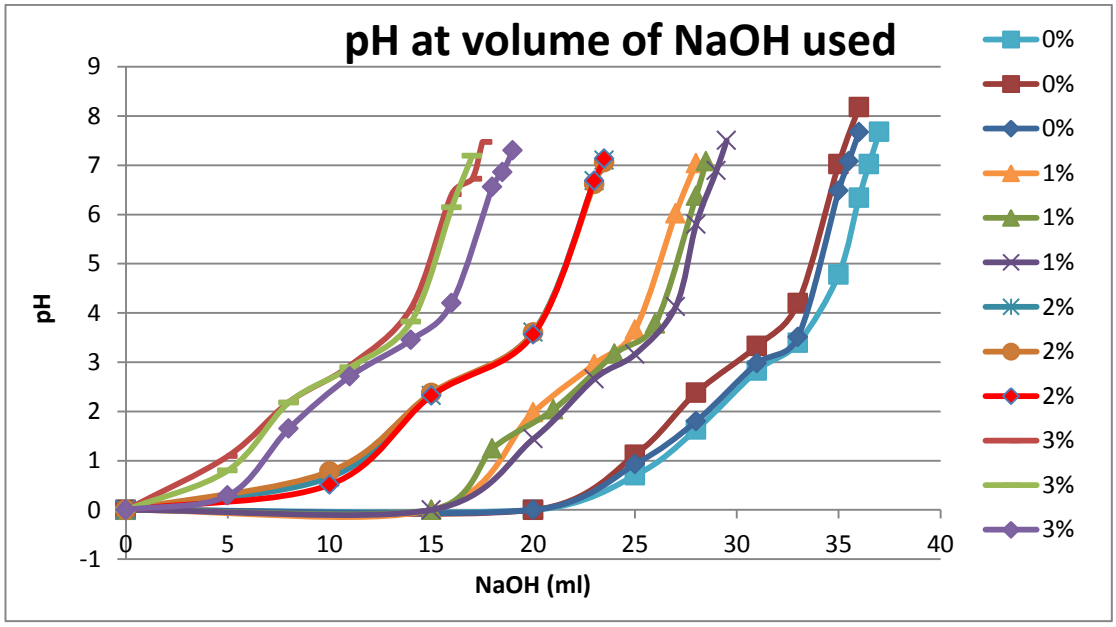

Figure 4-20: Results for High PI Gravel at 1 month hydration.

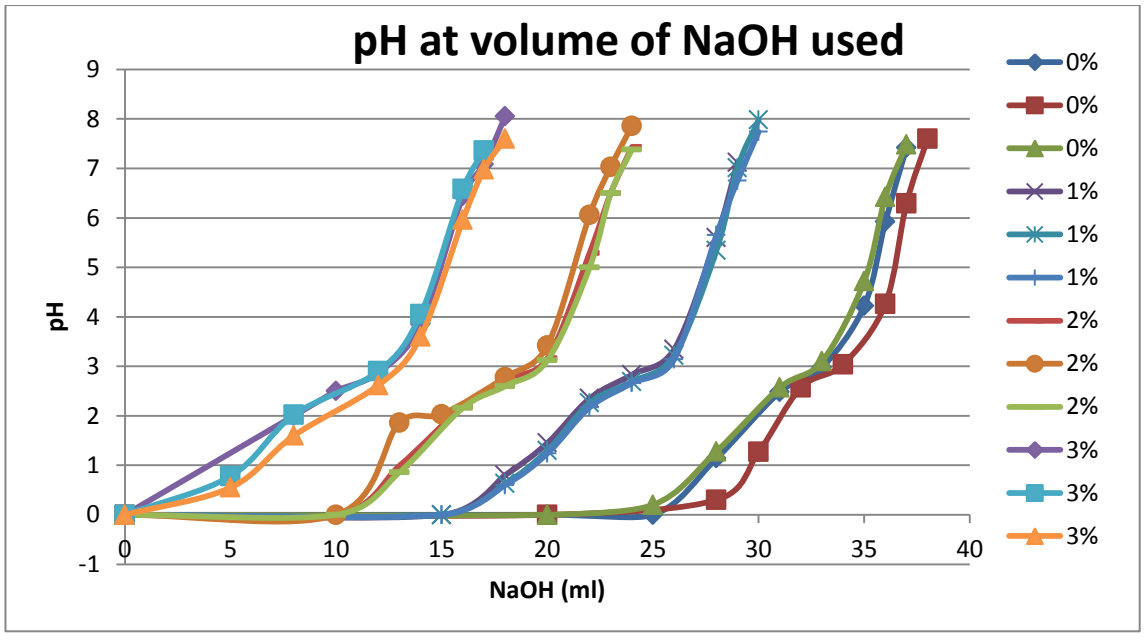

Figure 4-21: Results for High PI Gravel at 3 months hydration.

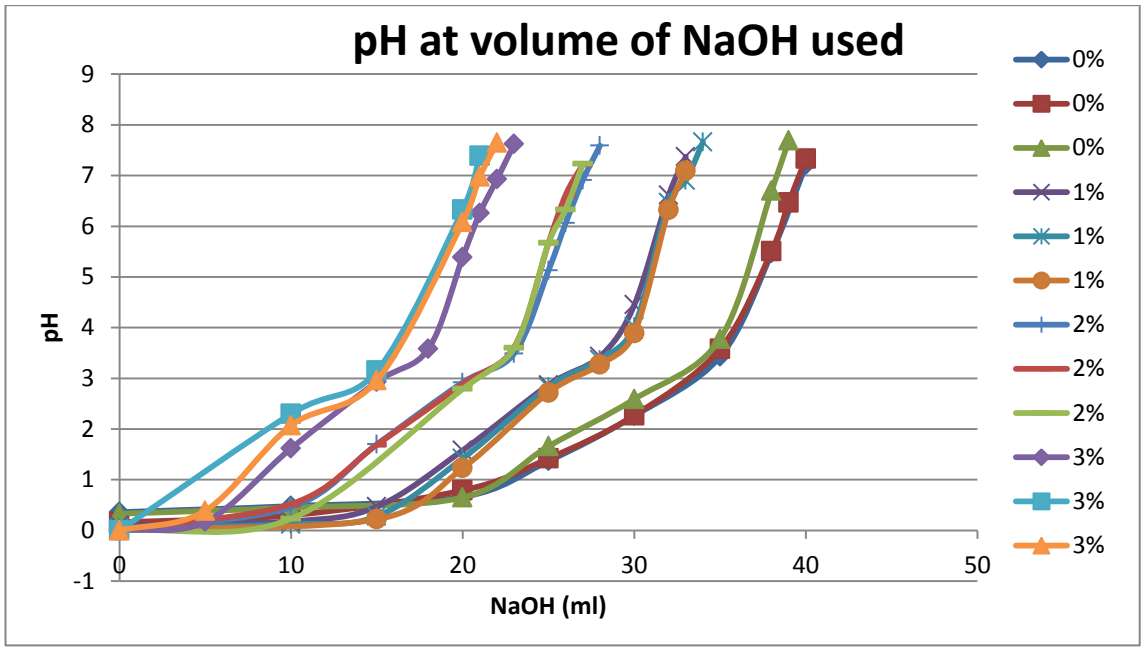

Figure 4-22: Results for High PI Gravel at 6 months hydration.

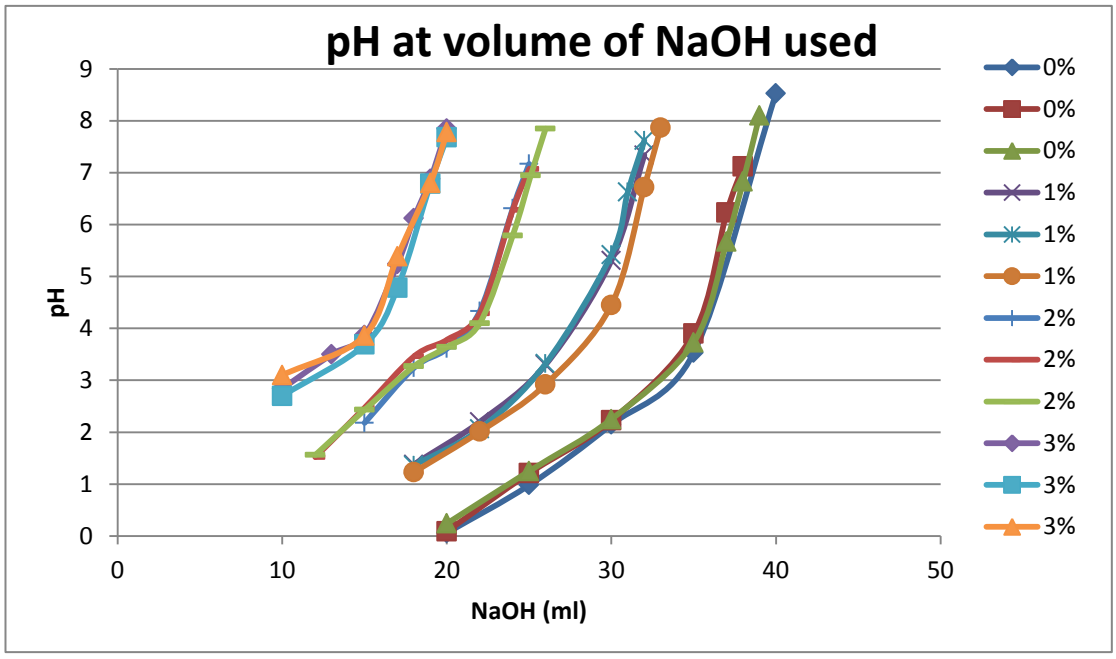

Figure 4-23: Results for High PI Gravel at 12 months hydration.

4.7.1 Results Analysis of High PI Lateritic Gravel Samples

The amount of NaOH consumed to achieve pH 7 was approximated from the graphed results. These approximated values were used to calculate the mean, standard deviation and the confidence interval of the mean using the formula from Equation 4-1, Equation 4-2 and Equation 4-3 and are shown in Table 4-17.

Table 4-17: Mean consumption of NaOH (mL), SD and CI for High PI Gravel samples.

Hydration Period	Cement	Mean	Standard Deviation	Confidence Interval
1 month	3%	17.63	0.95	±2.35
	2%	23.43	0.06	±0.14
	1%	28.57	0.60	±1.50
	0%	35.67	0.76	±1.90
3 months	3%	16.73	0.31	±0.76
	2%	23.33	0.29	±0.72
	1%	29.03	0.15	±1.31
	0%	36.90	0.53	±0.14
6 months	3%	21.23	0.68	±1.69
	2%	26.77	0.31	±0.76
	1%	32.83	0.31	±0.76
	0%	39.20	0.78	±1.94
12 months	3%	19.10	0.10	±0.25
	2%	24.90	0.10	±0.25
	1%	31.77	0.50	±1.25
	0%	38.20	0.36	±0.90

As can been seen from Table 4-17, the standard deviations for the High PI Lateritic Gravel samples are low and range between 0.06 and 0.95. This indicates a reasonable correlation exists between the test sample results.

The confidence intervals (shown in Table 4-17), calculated for the sample means suggest that the estimate of these means is reasonably precise and therefore this data can be used for further analysis.

These values were also used to calculate the Z scores using the formula from Equation 4-3, and are shown in Table 4-18.

Table 4-18: Z - scores for High PI Gravel samples.

Hydration Period	Cement	Z Score		
1 month	3%	1.13	-0.35	-0.78
	2%	-0.58	1.15	-0.58
	1%	1.05	-0.11	-0.94
	0%	-0.87	-0.22	1.09
3 months	3%	-1.09	0.22	0.87
	2%	-1.15	0.58	0.58
	1%	-0.87	-0.22	1.09
	0%	1.13	-0.38	-0.76
6 months	3%	1.13	-0.34	-0.78
	2%	1.09	-0.22	-0.87
	1%	0.87	0.22	-1.09
	0%	0.64	0.51	-1.15
12 months	3%	-1.00	0.00	1.00
	2%	-1.00	0.00	1.00
	1%	-0.93	-0.13	1.06
	0%	-0.83	-0.28	1.11

The highest Z score (shown in Table 4-18), is ±1.15 indicating that the test results for the High PI Lateritic Gravel samples are satisfactory with none having an absolute value ≥ 2; therefore all values can be used for further analysis.

The mean values taken from the graph were then used to determine the average amount of Hydrochloric acid consumed for each cement content percentage and can be seen in Table 4-19.

Table 4-19: HCl (mL) consumed based on mean results for High PI Gravel samples.

Hydration Period	% cement	HCl (mL) consumed
1 month	3	32.37
	2	26.57
	1	21.43
	0	14.33
3 months	3	33.27
	2	26.67
	1	20.97
	0	13.10
6 months	3	28.77
	2	23.23
	1	17.17
	0	10.80
12 months	3	30.90
	2	25.10
	1	18.23
	0	11.80

This data was graphed and a trend line added to demonstrate that a linear relationship existed between the amount of cement added and the amount of HCl consumed as can be seen in Figure 4-24.

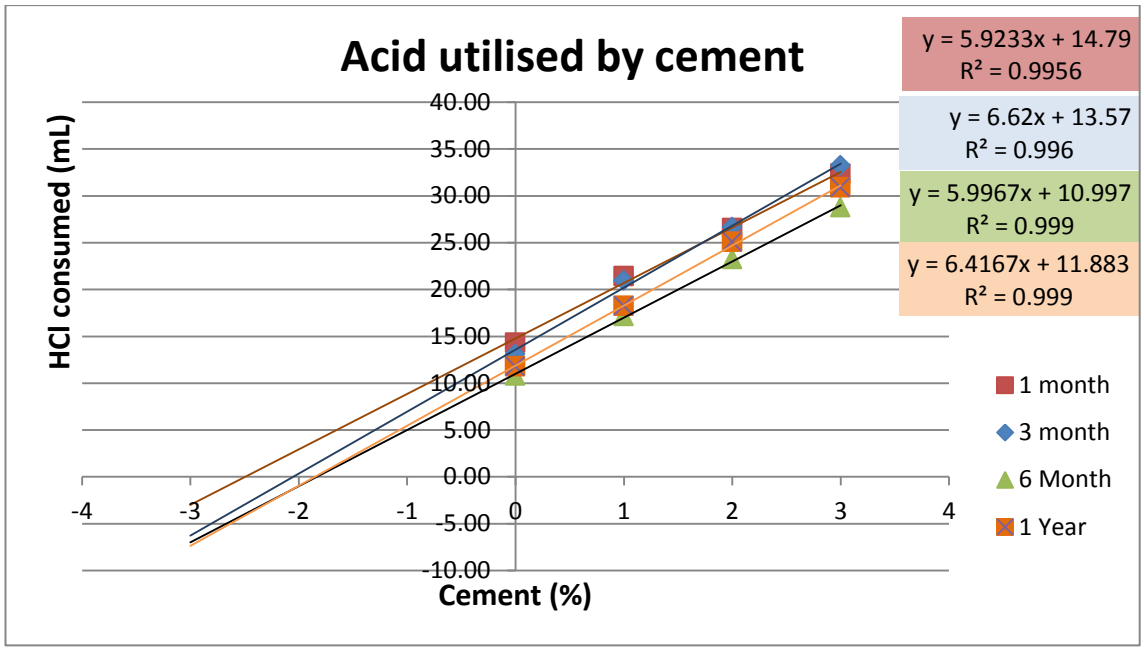

Figure 4-24: Graph of acid consumed by cement for High PI Gravel samples.

The linear trend line for the High PI Lateritic Gravel samples is a very strong fit to the data with R^2 values of 0.9956, 0.996, 0.999 and 0.999 confirming that a strong linear relationship does exist between the amount of cement added and the amount of HCl consumed. This relationship is significant in determining the amount of cement present in the test sample before cement addition occurred.

The linear trend line equations from Figure 4-24 were used to predict the original cement content of the samples and are shown in Table 4-20.

Table 4-20: Prediction of cement content from linear equations.

Hydration Period	Equation	Predicted cement content (%)
1 month	y = 5.9233x + 14.79	2.50
3 months	y = 6.62x + 13.57	2.05
6 months	y = 5.996x + 10.997	1.83
12 months	y = 6.4167x + 11.883	1.85

The actual cement addition at sample preparation was 2.5%.

The results for the Wheatbelt North High PI Gravel samples were very consistent with the actual cement addition for the initial testing at one month hydration and satisfy the requirement that the test method is reliable within an error margin of ±0.2%. The predicted cement content values then show a gradual decrease over the 3 and 6 month hydration periods and then appeared to plateau at the 12 month testing.

4.8 Discussion of Results

A very strong correlation between the percentage of cement added and the amount of Hydrochloric Acid consumed is evidenced throughout the testing of the four basecourse materials across the four hydration periods. The strong correlation evident has allowed linear regression analysis to be used to predict the original cement content of the samples.

4.8.1 Cement Content

The predicted cement content values achieved for the Mid-West Lateritic Gravel and the Wheatbelt North High PI Gravel basecourse materials at one month hydration were consistent with the actual cement addition of 2.5% and satisfy the requirement that the test method is reliable within an error margin of ±0.2%.

The predicted cement content values for these materials then decreased over the 3, 6, and 12 month hydration periods as shown in Table 4-21, and were no longer giving a reliable indication of the original cement content of the samples.

Table 4-21: Predicted cement content

Hydration Period	Predicted cement content (%) Wheatbelt North High PI Gravel	Predicted cement content (%) Mid-West Lateritic Gravel
1 month	2.50	2.44
3 months	2.05	2.25
6 months	1.83	2.17
12 months	1.85	1.91

The cement prediction values achieved for the Mid-West Lateritic Gravel were still dropping at the 12 month hydration test; however the values achieved for the Wheatbelt North High PI Gravel at the 6 and 12 month hydration periods give the impression that the cement content readings may have stabilised.

Further testing of the basecourse materials at 24 months hydration is recommended to determine if the tested cement content values will continue to decrease.

The predicted cement content values achieved for the CRB samples were higher than the actual cement addition at one month hydration and while decreasing over the subsequent hydration periods; continued to be higher than the actual cement addition of 2.5%. (Table 4-22)

Table 4-22: Predicted cement content for CRB

Hydration Period	Predicted cement content (%) Crushed Rock Base
1 month	3.09
3 months	3.03
6 months	2.89
12 months	2.69

Initially it was supposed that the high result for the one month hydration period test was caused by the change in the water used during the experiment; however further testing did not indicate that the water was affecting the results.

The successive testing of the CRB at 3, 6 and 12 months showed an incremental drop in the cement content readings as the hydration period increased, consistent with the similar behaviour of the Mid-West Lateritic Gravel and the Wheatbelt North High PI Gravel basecourse materials. This tends to suggest that the one month testing may have been accurate and that the raw CRB was somehow influencing the test results.

Further testing of the raw CRB will be required to determine why the results achieved are greater than the cement addition.

The cement content reading for the Crushed Rock Base, Mid-West Lateritic Gravel and the Wheatbelt North High PI Gravel basecourse materials reduced in a fairly consistent manner as the hydration period increased; however the results for the Pilbara Scree Gravel did not confirm this trend.

At one month hydration the predicted cement content values achieved for the Pilbara Scree Gravel at 2.15% were not consistent with the actual cement addition of 2.5% with an error margin of ±0.2%. The predicted cement content then fluctuated across the subsequent hydration periods as can be seen from Table 4-23.

Table 4-23: Predicted cement content for Pilbara Scree Gravel

Hydration Period	Predicted cement content (%) Pilbara Scree Gravel
1 month	2.15
3 months	1.90
6 months	2.17
12 months	1.73

The samples for the 3 month hydration period had to be remade and retested as a separate batch. This was because the test results from the original samples were flawed due to contamination of the source acid solution discovered during testing. The disparity of the results achieved for this basecourse material could be influenced by sample variation in the replacement 3 month samples arising from small inconsistencies with the sample preparation process.

Further testing of the Pilbara Scree Gravel will be required to determine why the results achieved are not consistent with the results from the other basecourse materials tested.

4.8.2 Equipment

The pH probe had to be replaced several times throughout the duration of testing due to failure evidenced by erratic readings. As a direct result of the probe failures the test procedure was altered slightly, this occurred midway through the test regime.

To raise the starting pH levels and help prolong the life of the pH probe the following amounts of sodium hydroxide were titrated into the sample;

- 20 mL for 0% cement addition
- 15 mL for 1% cement addition
- 10 mL for 2% cement addition
- 5 mL for 3% cement addition

This was to ensure the pH at the initial reading was not too low as highly acidic solutions can contribute to probe failure within a short period of time.

The pH meter was also replaced; however this occurred after most of the testing had been finalised. A replacement meter of similar calibre was used to complete the testing of the basecourse material.

4.8.3 Result Analysis

User bias in instrument readings and error margins due to approximations and assumptions being incorporated into the measurement method and procedure is unavoidable. The magnitude of the bias and error margins can be somewhat mitigated by representative lot testing being conducted by a single operator; however a reduction in test inconsistencies is desirable for future testing.

4.8.4 Procedure

Observations made during the testing led to the following procedural clarifications;

- Testing should be delayed for 8 - 12 hours after the addition of HCl to the test sample to ensure complete breakdown of the bound hydrated parent material.
- Inconsistent delays in testing create undesirable variation in test results; therefore consistency in timing of all test procedures is very important in order to obtain dependable results.
- As the Sodium Hydroxide solution reacts with carbon dioxide and water in the air and potentially changes concentration, it is necessary to conduct the testing within a narrow time frame. Any remaining sodium hydroxide solution dispensed from stoppered container should be discarded after testing.
- To ensure all HCl present in the test beaker has been exposed and reacted with the NaOH it is essential that the soil in the beaker is agitated and disturbed thoroughly before each reading.
- The time taken for the mixture to stabilise increases as the testing approaches pH neutral; therefore it is imperative that sufficient time be allowed and the mixture is fully agitated several times as it approaches neutral before recording the pH to ensure an accurate reading.

5. CONCLUSIONS

5.1 Summary of Investigations

A study into the determination of cement content of cementitious stabilised pavement was undertaken. The study included a review of the literature relevant to the cementitious stabilisation of new and existing pavement, as well as laboratory testing of typical West Australian basecourse materials. The focus of the investigation was the determination of the cement content of stabilised road base material utilising a test method trialled in 2009.

The investigation was performed in a number of stages with each stage building on the finds of the previous stage. The main focus areas were:

- Review stabilisation practices and methods currently adopted for determination of cement content.
- Perform testing on modified road base materials typically used in Western Australia to determine the range of application and establish the reliability of the test method.
- Analyse the test data using statistical analysis techniques to verify methods used and determine the consistency of the test method.

From the investigation undertaken a number of conclusions were made which are described in the following sections.

5.2 Cementitious stabilisation of pavement

Since its introduction in the 1940's for pavement construction and rehabilitation stabilisation has met with varying degrees of success throughout Australia; however technological advances combined with extensive research and pavement studies have led to an improvement in stabilisation practices. This has resulted in cementitious stabilisation being used more frequently across Australia for remedial and construction works.

Rehabilitation of the existing pavements by using cementitious stabilisation is becoming increasingly viable due to the social and environmental benefits. These include; reduced user impact; reduced need for quarried material; lower energy requirements and reuse of waste products. With limited road maintenance funding and increasing heavy vehicle axle loads reducing pavement life; cementitious stabilisation is also an ideal low-cost pavement rehabilitation technique that can improve the strength of the underlying granular material.

Testing of stabilised road base material is very important for predicting the future performance of the pavement. It is also an important diagnostic tool which can be used to help ascertain the cause of stabilised pavement failures.

5.3 Limitations of test method

In the course of this study the following conclusions were made following the laboratory testing of the limestone samples;

The test method as outlined in the methodology is not considered suitable for testing on granular pavement material with either; a high calcium carbonate content or granular pavement material whereby the material reacts strongly with hydrochloric acid to the extent that more than 10 % of the original mass is consumed.

The reasons are as follows;

- It was necessary to alter the molarities of the reagents and therefore the test method to accommodate materials that are highly reactive with hydrochloric acid.
- With reactive materials the mean results, determined by the test procedure, for HCl consumption across the differing cement concentrations were not distinct enough for linear regression analysis to be applied.

The initial testing of the Mid West Lateritic Gravel high plasticity road base material indicated that the test method was suitable for this type of road base material.

5.4 Long term veracity of test method

Using the test procedure as outlined in the methodology the following conclusions were made regarding the long term veracity of the test method;

- A very strong correlation between the percentage of cement added and the amount of Hydrochloric Acid consumed was evident throughout the testing of the four basecourse materials across the four hydration periods.
- Testing based on the results obtained for the Mid-West Lateritic Gravel and the Wheatbelt North High PI Lateritic Gravel samples indicate that the test method is reliable for these materials at one month hydration with an error margin of less than ± 0.2% (Table 5-1).

Table 5-1: Cement content determined for conforming test samples.

Parent Material	Cement Prediction (%)	Actual (%)	% difference
Mid-West Lateritic Gravel	2.44	2.5	+0.06
Wheatbelt North High PI Gravel	2.50	2.5	+0.00

- The predicted cement content values achieved for the Crushed Rock Base samples at 3.09% were higher than the actual cement addition of 2.5% at one month hydration and were not consistent with the required error margin of ±0.2% (Table 5-2).

- The predicted cement content values achieved for the Pilbara Scree Gravel samples at 2.15% were lower than the actual cement addition of 2.5% at one month hydration and were not consistent with the required error margin of ±0.2% (Table 5-2).

Table 5-2: Cement content determined for non-conforming test samples.

Parent Material	Cement Prediction (%)	Actual (%)	% difference
Crushed Rock Base	3.09	2.5	+0. 59
Pilbara Scree Gravel	2.15	2.5	-0.35

- The predicted cement content values achieved for all tested basecourse types then showed a marked decrease over the 3, 6 and 12 month hydration periods (Table 5-3).

Table 5-3: Cement content determined for test samples.

Hydration Period	Cement Prediction (%)			
	Crushed Rock Base	Pilbara Scree Gravel	Mid-West Lateritic Gravel	Wheatbelt North High PI Gravel
3 months	3.03	1.90	2.25	2.05
6 months	2.89	2.17	2.17	1.83
12 months	2.69	1.73	1.91	1.85

- From these results it has been concluded that the test method is not suitable for cement content determination where the hydration period is three months or longer.
- Results from the testing conducted in 2009 and current test results indicate that the test method is very suitable for testing for cement content of stabilised lateritic gravel basecourse at one month hydration.

5.5 Laboratory Testing

A number of issues were discovered during the laboratory testing of the basecourse materials. They included;

- Highly acidic solutions can contribute to probe failure within a short period of time. Consequently the pH probe had to be replaced several times throughout the duration of testing due to failure evidenced by erratic readings.
- Unforseen delays to testing created undesirable variation in test outcomes; therefore consistency in timing of all test procedures is very important in order to obtain dependable results.
- Additional samples of the basecourse materials had to been made up during the test procedure. Sample variation of replacement samples potentially leads to disparity in test outcomes.

6. RECOMMENDATIONS

Based on the conclusions drawn from the investigation the following recommendations are made for the pavement industry and future research projects in this area;

- The construction and rehabilitation of granular pavement using cementitious stabilisation methods should be promoted as a viable rehabilitation solution due to lower capital costs, improved long term performance and minimal disruption to the existing environment.

- Continued research into stabilisation processes should be promoted as they can potentially improve the performance and the cost of maintaining and upgrading the road network which is vital for the continued growth, prosperity and well-being of the Australian nation.

- Testing was conducted on samples containing only GP cement, however stabilised basecourse materials will often contain other additives to improve performance or workability. Further testing of basecourse samples containing General Blend and Low Heat cement would be beneficial to ascertain whether the test methods are valid over a range of improved basecourse materials.

- The method as outlined is appropriate for testing for cement content of stabilised in-situ basecourse, however initial testing using this method has only been conducted on prepared samples under laboratory conditions. It is recommended that field testing be conducted on stabilised in-situ lateritic gravel basecourse samples.

- Additional testing of the conforming lateritic basecourse materials is recommended to determine the maximum hydration period over which the predicted cement content values achieved are consistent with the actual cement addition and within the required error margin of ±0.2%.

- Additional testing at 24 months of the four basecourse materials trialled is recommended to determine if the predicted cement content values achieved by utilising the test method continues to decrease as the hydration period increases.

- Additional testing of the Pilbara Scree Gravel is recommended to determine why the results achieved are not consistent with the results from the other basecourse materials tested.

- Additional testing of the raw CRB is recommended to determine why the predicted cement content values achieved are greater than the actual cement addition.

- Expand the research to include other road base materials used in Western Australia.

- User bias in instrument readings and error margins due to approximations and assumptions being incorporated into the measurement method and procedure is unavoidable; however additional effort/measures to reduce test inconsistencies is desirable for future testing.

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APPENDIX A

TITRATION RESULTS

Titration results for Limestone, Sample Number # 09M153 – New Perth/Bunbury Highway Sub-base trial sections – Limitation testing.

Table A-1: Titration results for 2% cement addition

2%	Test 17	2%	Test 18	2%	Test 19
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0
1.34	5	ur	5	0.97	5
2.29	10	1.56	10	1.93	10
4.71	15	2.76	15	3.82	15
6.39	18	4.79	18	5.7	18
6.59	18.5	5.93	20	6.51	20
6.83	19	6.36	21	6.86	21
7.03	19.5	6.7	22	7.05	21.5
7.23	20	6.86	22.5	7.4	22
7.6	21	7	23		
		7.44	24		

Table A-2: Titration results for 3% cement addition

3%	Test 10	3%	Test 12	3%	Test 13	3%	Test 14	3%	Test 15	3%	Test 16
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
1.85	6	1.16	5	ur	5	1.87	5	1.28	5	0.85	5
2.34	9	2.15	8	1	10	2.67	10	2.04	10	1.92	10
2.66	12	2.5	10	1.95	15	3.78	12	4.06	15	3.22	15
4.05	15	2.77	12	2.56	18	4.73	14	5.39	17	5.16	18
5.18	17	3.29	15	3.1	20	6.06	16	6.28	19	5.71	19
5.78	18	4.67	17.1	4.35	22	6.8	17	6.63	20	6.29	20
6.23	19	5.27	18	5.46	24	6.87	17.15	6.82	20.5	6.69	21
6.63	20	5.95	19	6.25	26	6.96	17.3	6.89	20.7	6.97	21.5
6.98	21	6.45	20	6.68	26.5	7.45	18	7.5	22	7.21	22.1
7.24	22	6.88	21	6.93	27						
7.7	23	7.08	21.5	7.33	28						
		7.28	22	7.6	29						
		7.74	23								

Titration results for Wheatbelt North High PI Lateritic Gravel, Sample Number #09M276 Northam– Limitation testing.

Table A-3: Titration results for 0% cement addition

0% overnight		0%		0%		0%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	20	ur	25	ur	25	ur	25
0.51	25	0.42	28	1.32	30	2.8	33
2.43	30	1.55	30	3.32	35	3.7	35
3.12	32	2.79	32	6.86	37	6.84	37
3.7	34	3.44	34	8	38	7.95	38
6.35	36	3.9	35	9.24	39	9.05	39
6.65	36.2	5.6	36.2				
7.05	36.5	6.88	37				
		7.04	37.2				

Table A-4: Titration results for 1% and 2% cement addition

1%		1%		1%		2%		2%		2%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	15	ur	15	ur	15	ur	0	ur	0	ur	0
0.5	20	0.45	20	0.27	20	0.07	10	0.09	10	ur	10
2.2	23	2.81	25	2.83	25	1.81	15	1.98	15	1.66	15
3.01	25	3.48	27	3.43	27	3.31	20	3.35	20	3.16	20
3.63	27	6.26	29	5.96	29	5.3	23	5.93	23	5.21	23
6.28	29	6.78	29.5	7.1	30	6.68	24	6.98	24	6.54	24
6.98	29.5	7.08	29.8	8.36	31	6.87	24.3	7.97	25	7	24.5
7.44	30	8.45	31			7.13	24.5			7.53	25
8.47	31					7.39	25				

Table A-5: Titration results for 3% cement addition

3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0
1.96	10	1.89	10	1.89	10
3.34	15	3.31	15	3.22	15
6.45	18	6.35	18	6.25	18
7.02	18.6	6.85	18.5	6.87	18.6
7.4	19	7.32	19	7.3	19

Titration results for Mid-West Lateritic Gravel, Sample Number #08G192 – Geraldton Southern Transport Corridor (GSCT) Stage 2 at one month hydration.

Table A-6: Titration results for 0 % and 1% cement addition

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
ur	10	0.83	25	0.92	25	ur	10	ur	15	1.17	18
ur	20	2.93	30	2.86	30	ur	15	1.43	18	2.44	21
2.86	30	3.32	32	3.33	32	2.5	20	2.72	21	3.13	25
3.23	32	4.75	34	4.39	34	3.39	25	3.39	25	4.03	27
4	34	6.54	35	6.79	35	5.07	27	4.2	27	5.66	28
6.99	36	7.11	35.3	6.99	35.5	7.38	29	5.75	28	7.03	29
8.56	37			8.3	36			7.02	29		

Table A-7: Titration results for 2% and 3% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
1.05	10	1.09	10	1.02	10	1	5	1.84	5	1.71	5
2.84	15	2.82	15	2.76	15	3	10	2.88	10	2.81	10
3.18	17	3.13	17	3.08	17	3.16	12	3.24	12	3.1	12
3.4	19	3.38	19	3.41	19	3.34	14	3.84	14	3.6	14
4.31	21	4.27	21	4.44	21	4.32	16	6.26	16	5.8	16
6.9	23	6.89	23	6.66	23	5.88	17	7.04	17	6.9	17
7.8	24	7.84	24	7.88	24	6.75	18			7.75	18
						7.3	18.5				

Titration results for Crushed Rock Base (CRB), Sample Number #09M276 – New Perth/Bunbury Highway Trial Section – basecourse, sections 2 & 3 at one month hydration tested with distilled water.

Table A-8: Titration results for 0% and 1% cement addition with distilled water

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
0.26	20	0.36	20	0.28	20	ur	10	ur	10	ur	10
2.68	25	2.63	25	2.71	25	1.92	15	1.58	15	2.1	15
3.24	28	3.32	28	3.27	28	2.77	18	2.71	18	2.91	18
5.08	30	5.32	30	5.18	30			3.14	21	3.35	21
5.95	31	6.1	31	6.05	31			4.5	23	5.16	23
6.6	32	6.72	32	6.78	32			6.05	25	6.63	25
7.5	33	7.72	33	7.67	33			6.69	26	7.02	25.5
								7.23	26.5	7.92	26.5

Table A-9: Titration results for 2% and 3% cement addition with distilled water

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
2.24	10	2.3	10	2.26	10	2.78	5	2.45	5	1.7	5
2.92	12	2.98	12	2.87	12	3.3	8	3.06	8	2.78	8
3.25	14	3.34	14	3.22	14	3.64	10	3.3	10	3.13	10
3.73	16	3.77	16	3.65	16	4.48	12	4.52	12	3.65	12
5.53	18	5.64	18	5.3	18	6.62	14	6.64	14	5.63	14
6.38	19	6.07	18.5	6.13	19	6.78	14.5	6.87	14.5	6.54	15
6.78	19.5	6.5	19	6.66	19.5	7.13	15	7.26	15	6.99	15.5
7.16	20	6.83	19.5	7.05	20	7.96	16	8.09	16	8.03	16.5
8.16	21	7.16	20	8.05	21						
		8.25	21								

Titration results for Crushed Rock Base (CRB), Sample Number #09M276 – New Perth/Bunbury Highway Trial Section – basecourse, sections 2 & 3 at one month hydration tested with MEB ionised water.

Table A-10: Titration results for 0% and 1% cement addition with ionised water

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
ur	15	ur	15	0.02	15	ur	10	ur	10	ur	10
0.41	20	0.73	20	1.87	20	2.54	15	1.67	15	1.35	15
2.91	25	3.27	25	3.26	25	3	17	2.86	18	2.95	18
3.46	28	3.77	28	3.78	28	3.3	19	3.37	21	3.4	21
3.98	30	5.05	30	5.78	30	3.8	21	3.8	23	5.1	24
6.25	33	5.85	31	7.28	32	5.41	23	5.73	25	6.65	26
6.76	33.5	6.45	32	8.3	36	6.14	24	6.47	26	7.06	26.5
7.18	34	7.13	33			6.8	25	6.8	26.5		
8.07	35	8.02	34			7.17	25.5	7.17	27		
						7.61	26				

Table A-11: Titration results for 2% and 3% cement addition with ionised water

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
2.13	10	2.32	10	2.07	10	2.15	5	2.29	5	2.1	5
3.06	12	2.93	13	2.85	13	3.18	10	3.19	10	3.07	10
3.16	14	3.44	16	3.41	16	4.47	12	4.44	12	3.99	12
3.42	16	5.28	18	5.13	18	6.39	14	6.35	14	6.11	14
5.03	18	6.17	19	5.95	19	6.86	14.5	7.11	15	6.93	15
5.83	19	6.92	20	6.63	20	7.29	15	7.75	15.5	7.41	15.5
6.59	20	7.7	21	7.02	20.5						
6.95	20.5			7.5	21						
7.47	21										

Titration results for Wheatbelt North High PI Lateritic Gravel, Sample Number #09M276 Northam at one month hydration.

Table A-12: Titration results for 0% and 1% cement addition

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
ur	20	ur	20	ur	20	ur	15	ur	15	ur	15
0.7	25	0.93	25	1.12	25	1.25	18	1.44	20	1.98	20
1.63	28	1.8	28	2.38	28	2.04	21	2.66	23	2.96	23
2.83	31	2.98	31	3.33	31	3.17	24	3.16	25	3.66	25
3.39	33	3.51	33	4.2	33	3.78	26	4.13	27	6.02	27
4.78	35	6.48	35	7.02	35	6.38	28	5.8	28	7.04	28
6.34	36	7.08	35.5	8.18	36	7.08	28.5	6.89	29		
7.02	36.5	7.67	36					7.5	29.5		
7.68	37										

Table A-13: Titration results for 2% and 3% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
0.66	10	0.78	10	0.51	10	1.09	5	0.8	5	0.29	5
2.32	15	2.37	15	2.32	15	2.19	8	2.18	8	1.65	8
3.61	20	3.6	20	3.56	20	2.93	11	2.89	11	2.71	11
6.68	23	6.62	23	6.68	23	4.1	14	3.82	14	3.45	14
7.1	23.5	7.06	23.5	7.13	23.5	6.41	16	6.14	16	4.2	16
						6.72	17	7.19	17	6.56	18
						7.47	17.5			6.86	18.5
										7.3	19

Titration results for Pilbara Scree gravel, Sample Number #10M57 – SLK 1512.5 LHS 3700 m Great Northern Highway H006 at one month hydration.

Table A-12: Titration results for 0% and 1% cement addition

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
ur	20	ur	20	ur	20	0.77	15	0.57	15	0.6	15
1.33	25	1.4	25	1.44	25	1.28	18	1.4	18	1.39	18
1.73	28	1.84	28	1.97	28	2.35	21	2.24	21	2.38	21
2.8	31	3.05	31	3.13	31	3.09	24	3.07	24	3.03	24
4.35	34	4.4	34	4.67	34	4.6	27	4.61	27	5.08	27
6.96	36	7.25	36	6.3	35	6.98	29	7.07	29	7.27	29
7.82	37			7.42	36	7.98	30	8.31	30		

Table A-13: Titration results for 2% and 3% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
1.2	10	0.79	10	0.78	10	1.18	5	1.08	5	1.02	5
1.57	12	1.33	12	1.36	12	1.81	7	1.79	7	2.2	7
2.43	14	2.1	14	2.23	14	2.39	9	2.51	9	2.62	9
2.9	16	2.65	16	2.72	16	2.96	11	2.91	11	2.99	11
3.28	18	3.1	18	3.21	18	3.72	13	3.51	13	3.87	13
4.83	20	4.55	20	4.51	20	6.24	15	6.25	15	6.3	15
6.1	21	5.97	21	5.94	21	6.69	15.5	6.65	15.5	6.89	15.5
6.71	21.5	6.97	22	6.93	22	7.7	16.5	7.15	16	7.3	16
7.1	22	7.85	23	7.84	23			7.65	16.5		
7.5	22.5										

Titration results for Mid-West Lateritic Gravel, Sample Number #08G192 – Geraldton Southern Transport Corridor (GSCT) Stage 2 at three months hydration.

Table A-14: Titration results for 0% and 1% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
1.2	10	0.79	10	0.78	10	1.18	5	1.08	5	1.02	5
1.57	12	1.33	12	1.36	12	1.81	7	1.79	7	2.2	7
2.43	14	2.1	14	2.23	14	2.39	9	2.51	9	2.62	9
2.9	16	2.65	16	2.72	16	2.96	11	2.91	11	2.99	11
3.28	18	3.1	18	3.21	18	3.72	13	3.51	13	3.87	13
4.83	20	4.55	20	4.51	20	6.24	15	6.25	15	6.3	15
6.1	21	5.97	21	5.94	21	6.69	15.5	6.65	15.5	6.89	15.5
6.71	21.5	6.97	22	6.93	22	7.7	16.5	7.15	16	7.3	16
7.1	22	7.85	23	7.84	23			7.65	16.5		
7.5	22.5										

Table A-15: Titration results for 2% and 3% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
2.6	15	0.58	10	0.59	10	1.3	5	1.23	5	1.72	5
2.84	17	2.59	15	2.64	15	2.28	7	2.58	9	2.61	9
3.2	19	2.95	17	3.02	17	2.72	9	3.34	13	3.71	13
4.86	21	3.4	19	3.55	19	2.97	11	5.44	15	6.23	15
6.22	22	5.73	21	6.24	21	3.52	13	6.68	16	7.02	16
7.18	23	6.97	22	7.32	22	6.01	15	7.66	17	8.12	17
		7.79	23			7.05	16				
						8.05	17				

Titration results for Crushed Rock Base (CRB), Sample Number #09M276 – New Perth/Bunbury Highway Trial Section – basecourse, sections 2 & 3 at three months hydration.

Table A-16: Titration results for 0% and 1% cement addition

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
3.15	25	3.22	25	3.23	25	3.27	20	3.36	20	3.28	20
5.05	30	5.05	30	5.05	30	5.38	25	5.42	25	5.36	25
6.03	32	6.03	32	6.03	32	6.58	27	6.62	27	6.52	27
6.65	33	6.73	33	6.69	33	7.12	28	7.21	28	7.07	28
7.22	34	7.26	34	7.27	34						

Table A-17: Titration results for 2% and 3% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
3.33	15	2.97	15	3	15	3.34	10	3.44	10	3.41	10
5.64	20	5.38	20	5.53	20	5.54	15	5.63	15	5.61	15
6.45	21	6.13	21	6.35	21	6.83	17	7.04	17	7.02	17
7.16	22	6.85	22	7.08	22	7.67	18				
		7.46	23								

Titration results for Wheatbelt North High PI Lateritic Gravel, Sample Number #09M276 Northam at three months hydration.

Table A-18: Titration results for 0% and 1% cement addition

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
ur	20	ur	20	ur	20	ur	15	ur	15	ur	15
1.02	28	1.08	28	0.3	28	0.8	18	0.6	18	0.63	18
2.14	30	2.26	30	1.27	30	1.45	20	1.24	20	1.3	20
2.82	32	2.85	32	2.57	32	2.35	22	2.17	22	2.26	22
3.37	34	3.43	34	3.04	34	2.83	24	2.66	24	2.69	24
6.01	36	6.31	36	4.26	36	3.34	26	3.14	26	3.22	26
7.14	37	7.49	37	6.29	37	5.6	28	5.65	28	5.34	28
				7.6	38	7.12	29	6.75	29	7.01	29
								7.74	30	7.98	30

Table A-19: Titration results for 2% and 3% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
ur	10	ur	10	ur	10	2	8	0.78	5	0.55	5
0.99	13	1.86	13	0.86	13	2.5	10	2.02	8	1.6	8
2.19	16	2.03	15	2.16	16	2.87	12	2.9	12	2.62	12
2.74	18	2.78	18	2.6	18	3.85	14	4.05	14	3.6	14
3.16	20	3.42	20	3.12	20	6.44	16	6.58	16	5.96	16
5.29	22	6.06	22	5	22	7.08	17	7.36	17	6.98	17
6.5	23	7.03	23	6.5	23	8.05	18			7.6	18
7.43	24	7.86	24	7.38	24						

Titration results for Pilbara Scree gravel, Sample Number #10M57 – SLK 1512.5 LHS 3700 m Great Northern Highway H006 at three months hydration.

Table A-20: Titration results for 0% and 1% cement addition

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
2.27	30	2.1	30	2.18	30	2.75	25	1.63	20	1.65	20
3.62	35	3.53	35	3.6	35	3.44	28	2.94	25	2.86	25
6.45	38	6.36	38	6.51	38	5.25	30	3.49	28	3.56	28
7.45	39	7.49	39	7.47	39	7.13	32	5.57	30	5.4	30
								7.33	32	7.15	32

Table A-21: Titration results for 2% and 3% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
1.64	12	1.91	15	1.98	15	2.74	10	2.87	10	2.78	10
1.95	15	2.87	18	2.88	18	3.1	13	3.78	15	3.41	15
2.82	18	3.47	21	3.55	21	3.47	15	5.43	17	4.8	17
3.54	21	5.59	24	4.9	24	4.56	17	6.76	19	6.19	19
5.52	24	7.16	26	6.69	26	6.04	19	7.71	20	6.94	20
7.13	26			7.52	27	6.86	20			7.88	21
						7.54	21				

Titration results for Mid-West Lateritic Gravel, Sample Number #08G192 – Geraldton Southern Transport Corridor (GSCT) Stage 2 at six months hydration.

Table A-22: Titration results for 0% and 1% cement addition

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
1.7	0	1.8	0	1.75	0	1.8	0	1.84	0	1.89	0
1.76	5	1.91	10	2.2	20	1.86	5	1.92	5	2.03	10
1.82	10	2.22	20	4.43	30	2	10	2.06	10	3.75	20
1.93	15	3.03	25	5.02	35	2.29	15	2.33	15	4.67	25
2.12	20	4.48	30	6.02	36	3.89	20	3.86	20	5.1	28
2.74	25	5.17	35	7.14	37	4.34	22	4.4	22	6.6	30
4.1	28	6.02	36			4.6	24	4.61	24	7.55	31
4.53	30	7.18	37			4.88	26	4.82	26		
4.74	32					5.16	28	5.09	28		
4.97	34					6.77	30	6.77	30		
6.06	36					7.67	31	7.58	31		
7.05	37										

Table A-23: Titration results for 2% and 3% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
1.86	0	1.89	0	1.88	0	2.05	0	2.07	0	2.06	0
2.04	5	2.44	10	2.37	10	2.7	5	2.98	5	2.64	5
2.55	10	4.18	15	4.12	15	3.9	8	4.04	8	3.83	8
3.74	13	4.58	18	4.72	20	4.42	10	4.31	10	4.6	12
4.43	16	4.78	20	6.01	24	4.62	12	4.57	12	4.79	14
4.64	18	5.07	22	7.1	25	4.79	14	4.78	14	5.09	16
4.83	20	6.7	24			5.06	16	5.14	16	6.53	18
5.15	22	7.44	25			6.5	18	6.72	18	7.31	19
6.62	24					7.16	19	7.41	19		
7.47	25										

Titration results for Crushed Rock Base (CRB), Sample Number #09M276 – New Perth/Bunbury Highway Trial Section – basecourse, sections 2 & 3 at six months hydration.

Table A-24: Titration results for 0% and 1% cement addition

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
1.72	0	1.8	0	1.82	0	1.77	0	1.86	0	1.83	0
1.78	5	1.93	10	6.15	30	1.9	5	1.97	5	3.56	15
1.88	10	2.76	20	6.6	31	2.15	10	2.2	10	5.57	25
2.12	15	4.43	25	6.98	32	3.55	15	3.6	15	6.62	27
2.68	20	4.9	30			4.2	17	4.53	20	7.04	28
4.41	25	6	32			4.51	19	5.34	25		
4.67	28	6.82	34			4.67	21	6.08	26		
4.9	30	7.27	35			4.87	23	6.57	27		
5.95	32					5.61	25	7	28		
6.47	33					6.35	26	7.48	29		
6.86	34					6.71	27				
7.2	35					7.1	28				

Table A-25: Titration results for 2% and 3% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
1.97	0	1.98	0	1.97	0	2.12	0	2.31	0	2.19	0
2.43	5	2.55	5	2.38	5	3.52	5	4.08	5	3.85	5
4.15	10	4.47	10	4.21	10	4.36	8	4.6	10	4.52	10
4.67	15	4.78	15	4.68	15	4.56	10	6.48	15	5.66	15
5.08	18	5.5	18	6.09	20	4.74	12	7.05	16	6.48	16
5.96	20	6.53	20	6.58	21	5.02	14			7.04	17
6.5	21	6.92	21	7.01	22	6.26	16				
6.96	22	7.32	22			6.86	17				
7.58	23					7.31	18				

Titration results for Wheatbelt North High PI Lateritic Gravel, Sample Number #09M276 Northam at six months hydration.

Table A-26: Titration results for 0% and 1% cement addition

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
0.36	0	0.16	0	0.33	0	0.1	0	0.05	0	0	0
0.48	10	0.3	10	0.45	10	0.18	10	0.12	10	0.22	15
0.66	20	0.79	20	0.65	20	0.47	15	0.28	15	1.23	20
1.37	25	1.42	25	1.66	25	1.58	20	1.42	20	2.72	25
2.26	30	2.27	30	2.59	30	2.87	25	2.83	25	3.27	28
3.43	35	3.58	35	3.78	35	3.43	28	3.37	28	3.89	30
5.47	38	5.51	38	6.7	38	4.45	30	4.02	30	6.32	32
7.21	40	6.47	39	7.69	39	6.61	32	6.47	32	7.09	33
		7.33	40			7.37	33	6.9	33		
								7.66	34		

Table A-27: Titration results for 2% and 3% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	ur	0	ur	0	ur	0
0.46	10	0.52	10	0.23	10	0.17	5	2.3	10	0.39	5
1.7	15	1.69	15	2.79	20	1.62	10	3.15	15	2.07	10
2.92	20	2.89	20	3.6	23	2.93	15	6.33	20	2.96	15
3.49	23	3.62	23	5.67	25	3.58	18	7.39	21	6.08	20
5.13	25	5.67	25	6.33	26	5.39	20			6.98	21
6.06	26	6.62	26	7.23	27	6.26	21			7.65	22
6.91	27	7.22	27			6.93	22				
7.59	28					7.62	23				

Titration results for Pilbara Scree gravel, Sample Number #10M57 – SLK 1512.5 LHS 3700 m Great Northern Highway H006 at six months hydration.

Table A-28: Titration results for 0% and 1% cement addition

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
1.73	0	1.83	0	1.86	0	1.79	0	1.87	0	1.85	0
1.81	5	1.97	10	2	10	2.06	10	2.27	10	2.21	10
1.91	10	2.16	15	2.19	15	2.6	15	3.23	15	1.73	20
2.09	15	2.56	20	2.85	20	3.58	20	3.63	20	2.73	25
2.59	20	3.4	25	3.39	25	4.25	25	4.43	25	5.53	30
3.43	25	4.15	30	4.17	30	5.8	30	6.59	30	6.54	31
4.3	30	5.01	35	5.08	35	7	31	7.4	31	7.23	32
5.2	35	7.43	38	7.03	37	7.75	32				
7.39	38			7.68	38						

Table A-29: Titration results for 2% and 3% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
ur	0	ur	0	ur	0	1.29	0	0.22	0	0.67	0
0.72	10	0.85	10	1.09	10	2.29	5	1.54	5	1.52	5
2.17	15	1.84	15	3.08	20	3.46	10	3	10	2.9	10
2.93	20	2.83	20	6.45	25	4.21	15	3.69	15	3.72	15
6.2	25	6.1	25	7.3	26	6.25	18	5.38	18	5.62	18
6.99	26	6.98	26			6.99	19	6.31	19	6.36	19
7.78	27	7.78	27			7.66	20	6.92	20	7.01	20
								7.41	21	7.56	21

Titration results for Mid West Lateritic Gravel, Sample Number #08G192 – Geraldton Southern Transport Corridor (GSCT) Stage 2 at twelve month hydration.

Table A-30: Titration results for 0% and 1% cement addition

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
0.78	25	1.23	25	0.85	25	2.02	20	2.02	20	2.12	20
2.82	30	2.95	30	2.7	30	3.11	25	3.11	25	3.1	25
3.43	35	3.63	35	3.32	35	3.46	28	3.5	28	3.5	28
6.61	38	7.09	38	6.32	38	4.57	30	4.67	30	4.9	30
7.93	39			7.63	39	6.58	32	6.66	32	6.77	32
						7.63	33	7.67	33	7.84	33

Table A-31: Titration results for 2% and 3% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
2.57	15	0.51	10	0.44	10	2.57	8	0.37	5	2.78	8
3.07	18	2.61	15	2.53	15	3.12	12	2.55	10	3.14	12
3.27	20	3.05	18	3.06	18	3.47	15	3.24	15	3.58	15
3.73	22	3.29	20	3.28	20	5.88	18	3.97	18	5.94	18
5.6	24	3.63	22	3.66	22	7.37	20	5.8	20	7.45	20
6.68	25	5.33	24	5.36	24			6.76	21		
7.35	26	6.23	25	6.36	25			7.77	22		
		7.15	26	7.28	26						

Titration results for Crushed Rock Base (CRB), Sample Number #09M276 – New Perth/Bunbury Highway Trial Section – basecourse, sections 2 & 3 at twelve months hydration.

Table A-24: Titration results for 0% and 1% cement addition

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
1.65	20	1.46	20	2.02	20	2.93	15	0.85	10	0.85	10
3.1	25	3.09	25	3.1	25	3.56	18	3	15	3	15
3.5	28	3.49	28	3.56	28	3.76	20	3.89	20	3.85	20
4.46	31	4.5	31	4.48	31	3.96	22	4.05	22	4.04	22
5.4	33	5.42	33	5.46	33	4.38	24	4.94	24	4.62	24
6.36	35	6.37	35	6.17	34	5.89	26	6.03	26	5.86	26
7.11	36	7.18	36	6.96	35	6.44	27	6.49	27	6.38	27
				7.65	36	7.09	28	7.13	28	6.95	28
										7.54	29

Table A-25: Titration results for 2% and 3% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
2.67	10	2.66	10	2.64	10	2.32	5	2.61	5	2.64	5
3.32	15	3.33	15	3.25	15	3.17	10	3.2	10	3.2	10
3.72	18	3.72	18	3.63	18	3.48	13	3.72	13	3.7	13
5.12	20	5.1	20	4.9	20	4.47	15	5.13	15	5.1	15
5.66	21	6.4	22	5.84	22	5.69	17	6.18	17	6.2	17
6.16	22	6.87	23	6.45	23	7.01	19	7.02	18	7.06	18
6.86	23	7.6	24	7.24	24						
7.53	24										

Titration results for Wheatbelt North High PI Lateritic Gravel, Sample Number #09M276 Northam at one month hydration.

Table A-24: Titration results for 0% and 1% cement addition

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
0.06	20	0.09	20	0.24	20	1.38	18	1.36	18	1.23	18
0.98	25	1.21	25	1.25	25	2.2	22	2.06	22	2.01	22
2.15	30	2.23	30	2.25	30	3.3	26	3.32	26	2.92	26
3.53	35	3.9	35	3.73	35	5.31	30	5.42	30	4.45	30
8.53	40	6.23	37	5.67	37	7.34	32	6.63	31	6.72	32
		7.12	38	6.83	38			7.62	32	7.87	33
				8.1	39						

Table A-25: Titration results for 2% and 3% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
2.18	15	1.52	12	1.56	12	2.84	10	2.7	10	3.1	10
3.24	18	2.47	15	2.43	15	3.5	13	3.69	15	3.86	15
3.61	20	3.46	18	3.27	18	3.87	15	4.78	17	5.39	17
4.33	22	3.78	20	3.64	20	5.24	17	6.79	19	6.8	19
6.31	24	4.29	22	4.1	22	6.12	18	7.68	20	7.78	20
7.17	25	6.28	24	5.79	24	6.88	19				
		7.07	25	6.95	25.1	7.85	20				
				7.85	26						

Titration results for Pilbara Scree gravel, Sample Number #10M57 – SLK 1512.5 LHS 3700 m Great Northern Highway H006 at twelve months hydration.

Table A-24: Titration results for 0% and 1% cement addition

0%		0%		0%		1%		1%		1%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
0.78	20	0.87	20	0.77	20	1.68	15	2.36	15	4.8	30
2.05	25	1.99	25	1.87	25	2.62	20	3.24	20	6.68	32
2.97	30	2.96	30	2.73	30	3.62	25	4.15	25	8.5	33
4.05	35	3.98	35	3.75	35	4.7	30	4.95	30		
5.87	37	5.85	37	5.37	37	6.7	32	6.79	32		
6.9	38	6.74	38	6.49	38	8.58	33	8.65	33		
8.24	39	8.04	39	7.79	39						

Table A-25: Titration results for 2% and 3% cement addition

2%		2%		2%		3%		3%		3%	
pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH	pH	mL NaOH
2.53	10	2.18	10	1.94	10	3.84	10	3.85	10	3.72	10
3.56	15	3.14	15	3	15	4.76	15	4.69	15	4.48	15
4.44	20	4.1	20	4.27	20	5.48	17	5.8	17	5.2	17
5.69	22	7.12	25	6.89	25	7.76	19	6.85	18	7.24	19
6.6	23			8.55	26			8.14	19		
7.5	24										

APPENDIX B

VALUES FOR T-DISTRIBUTIONS

Table B-1: Values for t-distributions with ν degrees of freedom for a range of *one-sided* or *two-sided* critical regions

One Sided	75%	80%	85%	90%	95%	97.5%	99%	99.5%	99.75%	99.9%	99.95%
Two Sided	50%	60%	70%	80%	90%	95%	98%	99%	99.5%	99.8%	99.9%
1	1.000	1.376	1.963	3.078	6.314	12.71	31.82	63.66	127.3	318.3	636.6
2	0.816	1.061	1.386	1.886	2.920	4.303	6.965	9.925	14.09	22.33	31.60
3	0.765	0.978	1.250	1.638	2.353	3.182	4.541	5.841	7.453	10.21	12.92
4	0.741	0.941	1.190	1.533	2.132	2.776	3.747	4.604	5.598	7.173	8.610
5	0.727	0.920	1.156	1.476	2.015	2.571	3.365	4.032	4.773	5.893	6.869
6	0.718	0.906	1.134	1.440	1.943	2.447	3.143	3.707	4.317	5.208	5.959
7	0.711	0.896	1.119	1.415	1.895	2.365	2.998	3.499	4.029	4.785	5.408
8	0.706	0.889	1.108	1.397	1.860	2.306	2.896	3.355	3.833	4.501	5.041
9	0.703	0.883	1.100	1.383	1.833	2.262	2.821	3.250	3.690	4.297	4.781
10	0.700	0.879	1.093	1.372	1.812	2.228	2.764	3.169	3.581	4.144	4.587